

Repair Coatings and Recoat Interfaces on Aged Photopolymers: Surface Reactivation, Chemical Compatibility and Structural Recovery

A failure-locus framework from aged substrate identification to re-aged repair qualification

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Abstract

An aged printed photopolymer is not the same bonding substrate as a freshly printed surface. Conversion, oxidation, hydrolysis, contamination, extractive loss, absorbed water, residual stress, cracking and previous service can change surface reactivity and the load-bearing structure. Abrasion, cleaning, plasma or UV-ozone treatment, primer application and a compatible repair resin can improve a particular interface, but no treatment is universally beneficial. A high initial lap, shear or flexural result may reflect cohesive failure outside the interface, favourable specimen geometry or a repair material that has not itself been aged.

This review defines a non-compensatory qualification architecture for repair coatings and recoat interfaces on aged photopolymers. It treats the aged substrate as a measured material state; separates cleaning, mechanical preparation, chemical reactivation and coupling; requires repair-material compatibility and cure to be evaluated independently of apparent bond strength; and distinguishes local interfacial recovery from recovery of part-level stiffness, strength, toughness, dimensional function and failure mode. Direct evidence from aged and repaired 3D-printed methacrylate and permanent dental resins is combined with bounded adjacent evidence for polymer-surface activation. The repaired assembly must be re-aged and retested in the intended environment. No universal abrasion, plasma, primer, recoat-window, bond-strength, cure or service-life value is established.

Keywords: aged photopolymer; repair coating; recoat interface; surface reactivation; chemical compatibility; bond strength; structural recovery; re-ageing; failure locus

1. Significance and scope

Repair is often framed as a surface-bonding problem, but the decision is broader. A coating may adhere to the outer micrometres of an aged part while cracks, embrittlement, distortion or environmental damage continue beneath it. A strong interface may shift failure into a weak aged substrate without restoring part function. Conversely, an interface result below pristine strength may still be adequate for a nonstructural barrier repair if the correct functional requirements are met.

ER-230 addresses repair coatings and recoat interfaces applied after a printed photopolymer has aged or served. Its central decision is whether the substrate state, preparation, repair chemistry, cure, interface and recovered part function are all demonstrated before and after renewed ageing.

1.1 Corpus boundary

ER-013 retains self-healing and interlayer repair mechanisms within photopolymer networks. ER-036 retains rheology and recoating during layerwise manufacture. ER-053 retains build-platform adhesion. ER-072 retains general environmental ageing. ER-168 retains general coating and encapsulation qualification, including fresh surface cure state and residual-species migration. ER-195 retains general cure-shrinkage stress at dissimilar-material interfaces. ER-208 retains general surface-chemistry mapping. ER-221 retains adhesion to metal substrates; ER-222 retains adhesion to conventional thermoplastic and thermoset adherends, not aged printed photopolymers. ER-224 retains primer chemistry, coupling reactions, film thickness, cure compatibility and recoat windows. ER-225 retains plasma, corona and UV-ozone activation together with ageing, contamination, over-treatment and bond performance of the activated state. ER-230 is restricted to restoring an aged or service-damaged printed photopolymer through a repair coating or recoat interface and to proving retained local and structural recovery after re-ageing.

2. Define the aged substrate as a material state

Age is not adequately described by calendar time. Record the original resin and print state, service temperature and humidity, light or radiation exposure, immersion media, chemicals, load history, cleaning and sterilisation, contamination, and any previous repair. Measure damage relevant to the intended recovery: mass or moisture change, surface chemistry, roughness, hardness or modulus, colour where diagnostic, dimensions, cracks and residual mechanical performance.

The direct methacrylate study deliberately aged a printed provisional resin and compared surface treatments and repair materials [1]. A permanent printed-resin study used extensive thermocycling before pretreatment and repair [2]. These designs support the principle that preparation is evaluated on a declared aged state. Their dental materials and cycling histories do not define ageing equivalence for industrial photopolymers.

Where service history is unknown, stratify the uncertainty. A representative coupon aged from new can support mechanism development but cannot prove that an unknown returned part has the same damage distribution. Acceptance may require destructive witness testing, conservative classification or rejection of parts with damage beyond the repairable envelope.

3. Classify repair architecture and intended recovery

Distinguish a thin cosmetic or barrier recoat, a wear-surface renewal, crack filling, edge or feature rebuild, bonded patch and section replacement. State whether the repair is required to recover appearance, impermeability, electrical or chemical isolation, dimensional tolerance, local wear resistance, joint integrity or structural load capacity. These architectures impose different stress states and evidence needs.

Also distinguish adhesion to the original surface, adhesion to an exposed bulk section and bonding across a machined or fractured plane. Layer-line orientation and anisotropy may matter differently in each case. A repair material can be chemically similar to the original resin yet cure to a different modulus, shrinkage and thermal response. Similar product labels do not establish compatibility.

Direct repair studies show interaction among printed substrate, preparation and repair material [1,4,5]. Their outcomes support testing the complete repair system rather than ranking treatments independently of material pair and geometry.

4. Identify damage and the governing failure locus

Before preparation, map whether the limitation is surface contamination, oxidation, weak boundary layer, crack network, cohesive embrittlement, delamination between printed layers or dimensional distortion. After testing, classify failure as interfacial, cohesive in the aged substrate, cohesive in the repair, mixed, or remote from the repaired zone. A change from interfacial to cohesive failure can indicate improved attachment, but it does not by itself prove adequate part strength.

The additively and subtractively manufactured material study couples repair bond strength with failure-mode evaluation [3]. The permanent-resin study likewise reports shifts among adhesive, mixed and cohesive failure after pretreatment [2]. Such classification is essential, but the specimen geometry and stress concentration still constrain interpretation. Fractography or cross-sectional inspection should support the visual category where consequences are significant.

5. Separate cleaning, abrasion, activation and coupling

Surface preparation can perform at least four different jobs. Cleaning removes contamination. Abrasion changes area and topography and can remove an aged boundary layer. Activation changes chemical functionality and wetting. A primer or coupling layer provides chemistry intended to bridge a particular substrate and repair material. Combining all steps into one protocol prevents identification of the active mechanism and makes deviations difficult to assess.

Use factorial or staged controls where practical: cleaned only, mechanically prepared, activated, primed and combined states. Measure the state created by each step. Abrasion requires media, size, pressure, distance, duration and cleaning after treatment. Activation requires source, atmosphere, power or dose, distance and treatment time, together with delay before bonding. Primer requires identity, film application, drying and cure state.

Direct studies show that mechanical roughening plus an adhesive can outperform an untreated control in a specific printed permanent resin [2], while other material combinations show that repair-resin identity and substrate compatibility can dominate and that surface treatment is not uniformly beneficial [4]. Therefore no step should be treated as mandatory without a matched material-state comparison.

6. Integrate an activated state into the repair sequence

Where activation is selected as one step in repairing an aged substrate, its state at bonding must be measured under the ER-225 framework. ER-225 owns activation chemistry and the ageing, contamination, over-treatment and bond performance of the activated state. ER-230 asks only whether that controlled state is transferred into the declared repair sequence without an unrecorded delay, handling event or incompatible subsequent step.

Polymer UV-ozone work shows that treatment duration can lead to different cell-adhesion outcomes and supports measurement of the activation state [7]. It is ER-225-domain evidence and is not structural-bonding evidence. Direct vacuum-plasma work on one 3D-printed resin evaluates surface state, bond response and retention after thermocycling [8]. Neither source authorises a generic treatment. Within ER-230, record the ER-225-qualified state, treatment-to-repair interval and compatibility of the next repair step.

Record the treatment-to-repair interval and storage atmosphere. Use the chemistry or validated proxy required by ER-225, then pair the declared state with interface and re-ageing results. A low water contact angle or high surface energy is an intermediate observation, not an acceptance criterion for the repaired part.

7. Establish chemical compatibility before claiming bonding

The repair liquid, primer or cleaning solvent may swell, craze, plasticise or extract components from the aged substrate. Conversely, a highly converted surface may provide little residual functionality for covalent coupling. Filler content and accessible inorganic surface influence whether silane is useful. Inhibitors, pigments and residual contamination can interfere with repair cure.

Screen mass and dimensional change, visible whitening or cracking, hardness, local modulus and chemical extraction under the intended contact time. Inspect the interface for voids, incomplete wetting and a swollen or dissolved boundary. Confirm that the repair material cures against the aged substrate rather than only in bulk. Where chemical similarity is proposed as the mechanism, demonstrate relevant reactive groups or interpenetration instead of assuming them from trade names.

The conventional-to-printed provisional-resin study found material-dependent repair performance and supports compatibility as a first-order variable [4]. Recent resin-cement work found limited benefit from silane on filler-deficient printed substrates and a strong influence of cement selection [6]. These findings prevent universal claims for a primer class or chemical family.

8. Declare the aged-surface state at repair

ER-224 owns recoat windows, including primer chemistry, coupling, film thickness and cure compatibility. ER-168 owns the fresh printed surface cure state and residual-species migration. ER-230 begins only after service ageing or declared damage: the repair input is an aged surface that may be oxidised, depleted, contaminated, water-loaded or mechanically degraded.

Report the elapsed service and storage history only as context for the measured aged state. When abrasion exposes material beneath the aged surface, identify whether the newly exposed region is chemically and mechanically uniform. Any primer or recoat-window decision must be imported from an ER-224-qualified material pair; ER-230 then tests whether it remains valid on the declared aged substrate. A treatment validated on a fresh post-cured coupon cannot be assigned to an aged service part without bridging evidence.

9. Control repair cure, thickness and residual stress

The repair layer introduces its own conversion gradient, cure shrinkage, exotherm, oxygen inhibition and post-cure response. A thick patch and a thin recoat do not impose the same constraint. Cure through a pigmented or opaque repair, cure adjacent to an absorbing aged substrate and shadowed cure around complex geometry require direct verification.

Report repair-layer thickness and geometry, exposure spectrum and dose, temperature, atmosphere, incremental sequence and post-cure. Assess conversion or a validated cure proxy at the free surface, interior and interface when gradients are plausible. Examine warpage, edge lift and cracks after cure. ER-195 retains the general mechanics of cure-shrinkage stress; ER-230 requires only the evidence needed to show that repair cure did not create an unacceptable interface or distort the restored part.

10. Design geometry for load transfer

Repair geometry governs peel, shear, cleavage and stress concentration. Abrupt coating edges, short overlaps, sharp crack terminations and stiff patches can localise stress even when coupon bond strength is high. The printed part may also be anisotropic, so the repair plane and service load must be related to build orientation and layer direction.

Use screening coupons to compare chemistry, then use a geometry that reproduces the governing part-level load path. Record overlap, taper, fillet, repair thickness, crack removal and remaining-section dimensions. Evaluate both monotonic and cyclic loading if service demands it. A shear-bond test ranks a defined configuration; it is not a direct structural allowable.

Repair studies using shear and flexural configurations demonstrate why endpoint and specimen architecture must be retained with the result [1-5]. A repair that passes a small bonded area can still fail through peel or substrate fracture in the part.

11. Distinguish interfacial recovery from structural recovery

Interfacial recovery concerns attachment and failure at the repair boundary. Structural recovery concerns the response of the whole repaired component relative to the aged damaged state and an appropriate intact reference. Required measures may include stiffness, strength, strain at break, toughness, fatigue, impact, leak resistance, dimensions or the original functional output.

Report at least three baselines where feasible: intact unaged, intact aged and aged damaged before repair. Compare the repaired state with all three rather than only with the damaged specimen. State whether recovery is absolute, fractional or fit-for-purpose. A value exceeding the aged damaged baseline does not prove restoration to pristine performance, and pristine equivalence may not be necessary for a bounded nonstructural function.

The denture-base study evaluates flexural repair in a directly printed resin system [5], while the other direct sources largely use local bond metrics [1-4,6]. Together they support separating interface screening from recovered structural behaviour.

12. Re-age the complete repaired assembly

The repaired system contains at least three zones: aged substrate, repair material and interphase. Water uptake, thermal expansion, oxidation and modulus evolution can differ among them. Re-ageing can reduce attachment, grow cracks or shift the failure locus even if the initial repair result is strong.

Expose the cured repair to the intended humidity, immersion, temperature, light, cleaning, sterilisation and mechanical cycles in a service-representative order. Then repeat both interface and functional measurements. Studies that thermocycled the completed repaired assembly demonstrate this principle within dental conditions [3,5,8]. By contrast, [1] and [2] aged the substrate before repair and support only the pre-repair state discussed in Section 2. Their cycle counts are not service-life factors for other applications.

Where ageing is accelerated, document the assumed mechanism and check that the accelerated condition does not introduce a different damage process. Include interim measurements to distinguish gradual degradation from abrupt failure. No retained-strength percentage or cycle count is universal.

13. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Aged substrate	Original print state, exposure history, contamination, damage and residual properties	Treating calendar age as material state
Preparation	Cleaning, abrasion, activation and primer separately controlled and measured	Crediting an unexplained combined protocol
Compatibility and cure	Swelling, extraction, wetting, interfacial cure, thickness and residual-stress evidence	Inferring compatibility from product family
Interface	Appropriate bond configuration, failure locus and uncertainty	Treating one shear value as a material constant
Structural recovery	Intact, aged, damaged and repaired baselines under part-relevant load	Equating adhesion with restored part strength
Retained repair	Complete assembly re-aged and retested	Accepting initial recovery as service durability

The gates are independent. High initial bond strength cannot compensate for solvent damage, incomplete repair cure, cohesive failure of a degraded substrate, part distortion or rapid loss after re-ageing.

14. Minimum reporting set

Report original resin or formulation family; printer, orientation, layer thickness and exposed face; wash, drying and post-cure; original properties and dimensions; service and ageing history; contamination and damage mapping; repair classification and intended function; cleaning; abrasion media and parameters; activation source and parameters; treatment-to-bond delay; primer identity and application; repair-material identity; compatibility screening; repair geometry and thickness; cure spectrum, dose, temperature and post-cure; surface chemistry and topography before and after preparation; bond or fracture-test geometry, rate and environment; failure locus; structural baselines; recovered properties; re-ageing sequence; interim observations; final interface and part state; replicates and uncertainty.

Every numerical result must retain the substrate state, material pair, preparation, geometry, cure, test mode and ageing history. No roughness, contact angle, activation dose, primer film, bond strength, recovery fraction or cycle count becomes a transferable target when those qualifiers change.

15. Knowledge boundary

The corpus directly supports treating aged printed methacrylate and permanent resins as material-specific repair substrates [1-6,8]. It supports interactions among mechanical preparation, adhesive or primer, repair-material selection, thermocycling and failure mode. Flexural repair evidence supports moving beyond a local interface metric [5]. UV-ozone evidence supports measurement of activation and the risk of time- or dose-dependent state changes [7], while direct vacuum-plasma evidence links activation, bonding and thermocycling for one printed resin system [8]. The direct sources are concentrated in dental resins and specimen geometries. Their protocols and values cannot be transferred to industrial printed photopolymers without requalification.

16. Limitations

The direct evidence is dominated by dental methacrylate systems, shear-bond or flexural specimens, proprietary materials and water-based thermocycling. Sources [1]-[6] and [8] were read at full-text or full methods-and-results depth; source [7] was read at abstract plus publisher-metadata depth and is used only for its abstract-visible cell-adhesion and activation-state result. No common resin chemistry, printing route, ageing condition, surface treatment, repair material or load geometry spans the corpus. The UV-ozone source is adjacent polymer-surface evidence, and the direct plasma source concerns resin cement rather than a structural repair coating. Coupon bond values do not establish fatigue, impact, fracture resistance, dimensional recovery or service life. Unknown field histories may not be reproducible by laboratory ageing. The review provides no commercial repair recipe, universal primer, abrasion protocol, activation dose, bond threshold, recoat window or structural allowable.

17. Conclusions

Repairing an aged photopolymer requires qualification of a new material system: aged substrate, preparation, repair material and interphase. The substrate must be defined by exposure and damage state rather than age alone. Cleaning, abrasion, activation and coupling serve different functions and must be controlled separately. Chemical compatibility, interfacial cure, repair thickness, residual stress and geometry determine whether a strong coupon result can translate to the part. Interfacial recovery is not structural recovery. The completed assembly must be re-aged and retested, with the failure locus and recovered function compared against intact, aged and damaged baselines. A defensible repair claim is limited to the declared resin, ageing state, preparation, repair system, geometry, cure, load and renewed service exposure.

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