

Adhesion of Photopolymer Materials to Glass and Ceramics: Silanisation, Hydroxylation, Moisture and Interfacial Fracture

A surface-state and crack-path qualification architecture for hydroxylated inorganic adherends

Juan Seguro

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Correspondence: info@3Dresyns.com · www.3Dresyns.com

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Abstract

Adhesion of a photocurable coating or bonded feature to glass or ceramic is governed by the declared inorganic composition, phase, finish and hydroxylated surface state together with the coupling layer, photocurable network, cure history, environment and test geometry. A nominally clean glass surface may carry adsorbed water, alkali-rich alteration, organic contamination or a previous silane layer. A ceramic label may conceal a silicate glass, glass-ceramic, zirconia-rich surface or multiphase oxide. These states are not interchangeable.

This review defines a qualification architecture that separates cleaning, hydroxylation, roughening and silanisation; verifies coupling-layer chemistry and organofunctional compatibility; distinguishes wetting and cross-cut response from interfacial fracture; and follows crack path under moisture and cyclic loading. The evidence supports paired surface, cure and mechanical measurements across UV-cured glass coatings, silane-treated glass-ceramics and adjacent epoxy/glass fracture studies. It does not establish a universal silane recipe, hydroxyl density, roughness, coupling-layer thickness, cure schedule, humidity limit, fracture threshold, acceleration factor or service-life claim.

Keywords: photopolymer adhesion; glass; ceramic; silane; hydroxylation; moisture; interfacial fracture; crack path

1. Significance and scope

Glass and ceramic adherends are often grouped as polar inorganic surfaces, but their adhesion behaviour depends on more than that label. Composition controls hydrolytic stability and surface chemistry. Polishing, grinding, etching, firing and storage alter topography and contamination. Water participates in silane hydrolysis and condensation but can also plasticise an interphase or assist crack growth. Photocure can create conversion gradients and residual stress whose effects depend on coating thickness, restraint and flaw population.

ER-223 addresses the evidence needed to qualify photocurable interfaces on glass and ceramic adherends. It does not prescribe a commercial treatment or bonding process. Its central decision is whether composition, surface state, coupling-layer state, cure, environment, mechanical method and observed crack path form a traceable chain supporting the intended use.

1.1 Corpus boundary

ER-023, ER-037, ER-049 and ER-151 retain ceramic feedstocks, printing, green bodies, debinding and sintering. ER-053 retains generic substrate and build-platform wetting and adhesion. ER-165 and ER-186 retain structural joint design and general light-curable adhesive or bondline formulation. ER-221 retains metal-specific adhesion and ER-222 retains thermoplastics and thermosets. ER-072 and ER-170 retain general ageing and life-claim validity. ER-195 retains generic cure-shrinkage stress models, ER-208 retains general surface-chemistry metrology, and ER-224 retains primer architecture across substrate families. ER-223 is restricted to glass- and ceramic-specific surface state, coupling chemistry, moisture response and locus-resolved interfacial fracture.

2. Define the inorganic adherend as a material state

The adherend record should identify composition, product class, phase assemblage, thermal history, exposed face and finish. Soda-lime silicate glass, fused silica, a glass-ceramic and zirconia-bearing ceramic cannot be pooled. Even within one class, ion exchange, leaching, polishing residues, machining damage and storage can change the surface presented to the liquid.

Record cleaning, rinsing, drying, handling and elapsed time before coating. Surface chemistry and topography require separate measurements when either supports a mechanism. Becerra and co-workers treated soda-lime silicate glass as a declared substrate and compared coating and adhesion observations with thickness and method limitations [1]. Their solvent-cast PMMA system is adjacent evidence, but its explicit substrate definition illustrates why “glass” alone is not a qualification.

3. Separate cleaning, hydroxylation, roughening and activation

A process name does not identify the final surface. Cleaning may remove organics while leaving an ion-rich altered layer. Hydroxylation may improve the population of reactive surface groups while increasing adsorbed water. Roughening can increase apparent area and mechanical interlocking but may introduce flaws or retain debris. Etching can change both composition and topography.

Qualification should measure the change relevant to the proposed mechanism. Contact angle can reveal a wetting response but cannot establish silane condensation or absence of contamination. Roughness does not prove coupling and can obscure the actual crack path. Composition-specific treatment comparisons on glass-ceramics and zirconia-reinforced lithium silicate show that surface treatment, bonding agent and failure mode must remain attached to the material tested [8]. Those dental procedures are not general coating instructions.

4. Treat silanisation as a sequence of states

Silanisation comprises hydrolysis, transport to the surface, adsorption, condensation with the inorganic surface, lateral condensation, drying and presentation of an organofunctional group to the overlying network. Nominal silane identity does not show which of these occurred. Excess water, insufficient hydrolysis, premature oligomerisation or an over-thick deposit can change the interphase without changing the product name.

Osoptasit and co-workers varied water amount and hydrolysis time and measured silane species, bond response and mixed failure on lithium-disilicate glass-ceramic [4]. That study supports state-resolved control of hydrolysis and condensation. Its numerical optimum, dental preparation and test geometry do not transfer. Dalle Vacche and co-workers used a reactive silane within a compositionally graded UV-cured glass coating [2], supporting the need to verify coupling and photocure together rather than treating silane application as an independent guarantee.

5. Verify the coating-facing function of the coupling layer

Anchoring to an oxide surface is only one side of the interphase. The outward-facing group must remain accessible and chemically compatible with the declared photocurable network. It may copolymerise, react through another route, remain physically associated or become buried within a condensed layer. A surface that carries silicon is not automatically a functional coupling surface.

Useful controls include the prepared substrate without silane, the silane-treated substrate before coating, a non-reactive or mismatched coupling-layer comparator and the cured coating away from the interface. Spectroscopy, extraction resistance, conversion measurements and locus-resolved fracture can provide complementary evidence. A strength increase without chemical or crack-path evidence cannot identify the mechanism.

6. Distinguish wetting from interfacial resistance

Wetting governs initial contact but not the durability or fracture resistance of the interface. Contact angle depends on liquid composition, roughness, heterogeneity, adsorption and time. Cross-cut or tape response is also method-specific and may be limited by coating cohesion, cut geometry or visual classification.

Cheng and co-workers evaluated UV-cured silicone-modified polyacrylate coatings on glass using cure, optical, water-uptake and adhesion observations [3]. Becerra and co-workers explicitly discussed the limits of qualitative tape testing [1]. These studies support paired response measurements but do not convert wetting or a cross-cut class into interfacial fracture energy.

7. Measure cure state near the inorganic interface

Glass transmission, ceramic scattering, pigments, reflection and specimen thickness can make the interfacial optical history differ from the exposed surface. Oxygen, heat flow and coupling-layer absorption can also affect conversion. Report source spectrum, irradiance, exposure, geometry, atmosphere, temperature, film or bondline thickness and post-exposure history.

Where a conversion gradient is plausible, measure near-interface cure or state the unresolved depth. Dalle Vacche and co-workers coupled UV cure, reactive-silane chemistry, coating gradients and mechanical glass response [2]. Cheng and co-workers linked formulation and UV-cured coating properties on glass [3]. Their specific cure conditions remain quarantined; the transferable point is that surface coupling and network formation must be qualified together.

8. Preserve thickness, restraint and residual-stress context

Coating thickness changes light absorption, defect population, bending stiffness and the stored energy available for delamination. Cure shrinkage becomes stress only through restraint, modulus development, geometry and relaxation. Thermal mismatch and post-cure may add or relieve the driving force. A strength value without thickness and specimen geometry is therefore incomplete.

For thin coatings, map thickness and continuity rather than report only a nominal application setting. For bonded specimens, report overlap or crack geometry and adherend compliance. No universal thickness or cure-stress threshold follows from the present evidence.

9. Use fracture and failure locus to identify the weak path

A terminal shear or pull-off value does not establish which interface failed. Post-test inspection should distinguish separation at the inorganic surface, within a coupling layer, at the coupling-layer–photopolymer boundary, cohesively in the photocured material, within a weakened glass or ceramic surface, and in the fixture adhesive. Mixed failure should be quantified or bounded.

Interfacial fracture methods can add crack-growth resistance and crack-path information, but their geometry and loading assumptions must be declared. Ritter and co-workers examined moisture-assisted crack growth at epoxy–glass interfaces and distinguished untreated, silane-bonded, fused-silica and soda-lime systems [5]. The values are not transferable to photocurable coatings, but the crack-path discipline is directly relevant.

10. Treat moisture as an interphase variable

Moisture can adsorb at hydroxylated surfaces, hydrolyse susceptible bonds, plasticise a polymer-rich interphase, transport ions and alter residual stress. Its effect depends on activity, temperature, exposure time, stress and access path. A lower terminal strength after immersion does not by itself reveal which process controlled the change.

Conditioning records should identify medium, temperature, duration, specimen stress state and whether edges were exposed. Repeat relevant surface or chemical measurements and the same mechanical method after conditioning. Dalle Vacche and co-workers linked a

hydrophobic UV-cured glass coating with water-barrier and mechanical observations [2], while Ritter and co-workers studied environment-controlled crack growth [5]. Neither establishes a universal humidity limit or acceleration factor.

11. Separate static and cyclic crack growth

Static loading, cyclic loading and one-time fracture interrogate different damage histories. A cyclic result requires load ratio or waveform, frequency, environment and crack-length method; a static crack-growth result requires the applied driving-force history and crack path. Final survival alone cannot distinguish slow interfacial growth from cohesive damage or substrate fracture.

Ritter and co-workers treated fatigue of silane-bonded epoxy/glass interfaces separately from static crack growth and recorded humidity or immersion and crack-path transitions [6]. This historical epoxy/glass work is adjacent evidence. It supports separate gates for cyclic and static durability, not a photocurable-interface fatigue limit.

12. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Adherend state	Composition, phase, finish, treatment, contamination and elapsed time	Treating all glass or ceramic as one substrate
Coupling layer	Hydrolysis/condensation evidence, deposition state and coating-facing function	Accepting nominal silane identity as proof
Cure state	Interfacial optical history, conversion endpoint and thickness	Inferring interface cure from the top surface
Mechanical response	Declared geometry, uncertainty and failure or crack locus	Converting cross-cut or shear into fracture resistance
Durability	Moisture and static/cyclic history with repeated locus-resolved testing	Converting initial adhesion into service life

The gates are independent. Better wetting cannot compensate for an unverified coupling layer, and a high initial strength cannot waive crack-path or moisture controls. Zhao and co-workers demonstrated photopolymerised adhesion across smooth and rough surfaces including glass and ceramics [7]; those cross-substrate results reinforce the need to retain chemistry, roughness, environment and geometry rather than collapse them into a universal ranking.

13. Minimum reporting set

Report glass or ceramic composition, phase and product class; exposed face and finish; polishing, grinding, etching, cleaning and storage; surface chemistry, hydroxylation proxy, contamination and topography; coupling-agent class, hydrolysis and deposition state, drying and delay; photocurable formulation identity; source spectrum, irradiance, exposure, atmosphere, temperature and post-cure; coating or bondline thickness; specimen and crack geometry; loading mode, rate or cyclic history; environment; replicates and uncertainty; failure or crack locus; and application-specific acceptance criteria.

Every numerical result must retain substrate composition, surface state, coupling layer, formulation, cure, thickness, environment, geometry and locus. No value should be presented as transferable when any of those qualifiers changes.

14. Knowledge boundary

The evidence establishes that glass composition and surface preparation belong to the adherend definition [1,8]; that reactive-silane state and photocure must be considered together [2,4]; that wetting and cross-cut response are not interfacial fracture measures [1,3]; that moisture can change crack growth and crack path [5]; that cyclic and static growth require separate treatment [6]; and that photopolymerised adhesion remains chemistry-, roughness- and environment-specific [7]. These propositions are bounded against generic adhesion, ceramic processing, joint design, primer architecture and general ageing ownership retained by the neighbouring ER corpus.

15. Limitations

The sources span solvent-cast PMMA, UV-cured glass coatings, dental glass-ceramics, epoxy/glass fracture and supramolecular photopolymer adhesives. Six sources were inspected at full-text depth and two through publisher abstract or bibliographic depth. The abstract-depth sources support only the propositions visible at that depth. No common round-robin substrate, coupling protocol, fracture geometry or durability model is established. The corpus does not establish a commercial treatment recipe, universal hydroxyl density, roughness, silane-layer thickness, hydrolysis condition, adhesion threshold, moisture limit, acceleration factor or service life.

16. Conclusions

Photopolymer adhesion to glass and ceramics must be qualified as a coupled surface-state, interphase, cure and fracture problem. Composition and finish must be explicit. Cleaning, hydroxylation, roughening and silanisation are distinct operations whose effects require measurement. A coupling layer must be verified on both its inorganic-facing and coating-facing sides. Wetting and cross-cut observations cannot substitute for locus-resolved mechanics. Moisture and cyclic loading can change both crack-growth rate and crack path, so durability requires declared conditioning and remeasurement. The resulting qualification is specific to the substrate, coupling layer, photocurable network, cure, geometry and environment and provides no universal recipe or threshold.

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