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removal difficult and increase shrinkage-related deformation. The same paper shows that the platform raising speed changes the load acting on the first layer, so an exposure value cannot be interpreted independently of motion history [3].

Paral et al. reviewed high-speed projection VPP and likewise framed the process as a competition between adhesion to the build plate or preceding layer and adhesion/separation at the transparent vat interface [4]. This is the key distinction from a conventional adhesive coupon: during printing, the desired interface is loaded repeatedly while an opposing interface is intentionally being detached.

Accordingly, a first-layer qualification record must include not only resin and exposure but also substrate material and finish, platform speed/acceleration, vat-interface condition, first-layer geometry, number of base layers, temperature, viscosity and observed detachment location. ER-34 addresses the vat-film separation mechanics themselves; ER-53 asks whether the desired substrate interface survives that known competing load.

4. Wetting and surface energy: necessary information, not a strength claim

Wetting controls whether the liquid resin can establish intimate contact with the substrate before gelation. Contact angle is therefore a useful process-state observable, but its interpretation depends on the probe liquid, surface cleanliness, roughness, time and model used to calculate surface-energy components. A low contact angle can improve contact without guaranteeing chemical coupling or resistance to residual stress.

Curley and Szczepanski demonstrated that substrate surface energy can influence the composition developed at a photopolymerising interface [5]. In their glass-versus-stainless-steel curing geometry, differences in interfacial energy directed component migration and produced compositionally different surfaces. The study is not a build-platform adhesion test, but it is important mechanistic evidence: the interface present after cure need not have the same composition as the bulk resin, and substrate choice can participate in that evolution.

This matters for VPP formulations containing polar monomers, oligomers, reactive diluents, particles, surfactants or adhesion promoters. A formulation may wet two substrates similarly yet develop different interfacial composition, conversion or residual stress. Contact-angle and surface-energy measurements should therefore be paired with chemical or mechanical evidence when a permanent adhesion claim is intended.

5. Chemical coupling and surface treatment

5.1 Silanisation and plasma activation

Izard et al. quantified adhesion of two-photon-polymerised microstructures to glass and reported substantially higher adhesion after treatment with an acryloxy-silane promoter; their surface-free-energy analysis supported a chemical contribution consistent with covalent coupling [2]. Kilic et al. subsequently used oxygen-plasma activation followed by methacrylate silanisation of glass before 2PP printing, illustrating how this preparation route has become part of high-resolution photopolymer workflows [6].

The newest direct evidence is the 2026 study by Roig et al., which compared plasma-activated silicon, ITO-coated glass, silane-functionalised silicon and an SU8-coated silicon interlayer using lateral shear of printed microstructures [1]. Silanisation improved adhesion, but solvent exposure compromised its stability in that system. The SU8 interlayer retained stronger adhesion through the tested post-processing sequence. This result is particularly important because it rejects the assumption that the treatment producing the highest initial adhesion must also provide the most durable interface.

5.2 Reactive promoters and interlayers

UV-curable coating literature provides adjacent mechanistic evidence. Wang et al. designed a methacrylate-functional adhesion promoter for UV-cured coatings on metal and showed that a reactive molecule can participate in cure while also interacting with the substrate [9]. The exact chemistry and coating geometry are not VPP build-platform conditions, so the result cannot be transferred quantitatively. It does, however, support the broader design principle of a reactive bridge between substrate-affine functionality and the cured network.

Polymeric interlayers can also redistribute stress, modify local cure and provide a chemically compatible surface. Their benefit must be separated from simple roughness changes. If an interlayer is used, its thickness, cure state, solvent history and own adhesion to the underlying substrate become additional interfaces in the evidence chain.

6. Roughness, geometry and residual stress

Surface roughness can increase true contact area and mechanical interlocking, but it can also introduce voids, nonuniform optical contact and stress concentrations. A single roughness amplitude is therefore not a universal predictor of adhesion. The direction and scale of texture should be reported together with the feature/contact size.

Roig et al. found geometry-dependent adhesion in 2PP microstructures, with cylindrical structures outperforming cubic structures under their lateral-shear protocol because the geometry reduced residual-stress concentration [1]. This demonstrates that the observed "adhesion strength" is a property of an interface-specimen-loading system, not of the resin/substrate pair in isolation.

Jeske et al. further showed that the contact topology and polymer mechanical state can be deliberately used to switch adhesion of 2PP-fabricated surfaces [7]. Their system is not a build-platform test, but it reinforces a critical qualification rule: contact area, modulus, temperature and geometry can alter measured adhesion independently of interfacial chemistry.

Network toughening strategies that raise fracture resistance without sacrificing conversion are reviewed by Ligon-Auer et al. [8]; a tougher bulk network changes which failure plane controls part removal.

7. Interfacial cure state and exposure

Exposure affects build adhesion through several coupled routes: the amount of polymer formed at the substrate, the local modulus, shrinkage stress, residual functionality and the thickness/geometry of the first cured region. Choi et al. directly showed an exposure threshold for initial adhesion in their DLP system and also identified overexposure as a source of distortion [3]. This creates a practical optimum rather than a monotonic "more exposure is better" rule.

For a transparent substrate, optical transmission, reflection and the direction of illumination can modify the interfacial dose. For opaque or absorbing substrates, the interface may be the lowest-dose region depending on exposure direction. Pigments, fillers and photoabsorbers can further alter the local dose. ER-27 remains the controlling paper for conversion metrology; ER-53 requires conversion or cured-state evidence only when needed to explain an adhesion result.

A post-cure may increase bulk conversion without recreating intimate contact or covalent coupling at an already separated interface. Conversely, a secondary thermal or photochemical reaction can continue across a contacting interface if reactive groups and mobility remain. The treatment must therefore be described mechanistically rather than as a generic "post-cure".

8. Measurement architecture

Table 2. Minimum measurement stack for a defensible substrate-adhesion claim

Layer	Recommended record	Decision value
Substrate state	Material/grade; cleaning; roughness/topography; treatment; storage time after treatment.	Defines the actual surface tested.
Liquid-interface state	Resin batch/state; temperature; viscosity; contact angle where relevant; time before cure.	Separates wetting from cured adhesion.
Cure state	Wavelength; irradiance/exposure; first-layer strategy; post-cure; interface optical path.	Links the interface to polymerisation state.
Mechanical test	Pull-off, lap shear, lateral shear, peel or custom VPP fixture with full geometry and rate.	Provides a declared load-mode endpoint.
Failure location	Adhesive, cohesive polymer, primer/interlayer, substrate, mixed, indeterminate.	Prevents mislabelling a cohesive failure as interface strength.
Conditioning	Dry/wet; solvent; temperature; UV; humidity; sterilisation if relevant; dwell.	Tests retention rather than only initial adhesion.
Statistics	Replicates; individual values; uncertainty/CI; censoring if substrate/cohesive failure limits measurement.	Supports reproducibility and avoids false precision.

8.1 Contact angle and surface energy

Use contact angle to document wetting under a declared procedure. If surface energy is calculated, report the model, probe liquids, droplet age, roughness state and number of replicates. Do not infer bond strength from surface energy alone.

8.2 Normal pull-off

ISO 4624:2023 specifies pull-off methods for coatings and is useful as an adjacent framework for rigid or deformable substrates [S1]. ASTM D4541-22 similarly covers pull-off strength of coatings from metal substrates and emphasises that apparatus, glue, cure time, pull rate and environment can change the result [S2]. A VPP part may be much thicker and more structured than a coating, so direct adoption requires a justified specimen design and explicit failure-location reporting.

8.3 Lap shear

ISO 4587:2003 specifies tensile lap-shear testing of rigid-to-rigid bonded assemblies and remains current while under systematic review [S3]. It is useful when the application resembles a bonded structural overlap. It does not provide design information and should not be treated as a dedicated VPP interface standard.

8.4 Microstructure shear and application-specific tests

For 2PP and small attached features, lateral shear can be more practical than attaching a pull-off dolly. Roig et al. and Izard et al. provide direct examples of microstructure-scale quantitative adhesion testing [1,2]. If the actual application is peeling, bending, fluid pressure, thermal cycling or repeated insertion/removal, an application-specific test should be added rather than forcing every interface into a single strength number.

9. Ageing and environmental durability

Initial adhesion and retained adhesion are separate claims. Solvents can alter a silane layer or swell the polymer; water can plasticise a polar network or change hydrogen bonding; heat can relax residual stress or accelerate interfacial degradation; UV can change the network and surface chemistry. Roig et al. provide direct evidence that the ranking of surface treatments can change after solvent/thermal processing [1].

A minimum durability study should predefine the relevant environment and repeat the same interface-sensitive mechanical test after conditioning. If failure migrates from the interface into the bulk, report that transition rather than merely recording a higher load. ER-41 controls general chemical resistance and solvent uptake; ER-72 controls broader environmental ageing and property retention. ER-53 uses those environments only to ask whether the substrate interface remains the controlling failure plane.

10. Qualification matrix

Table 3. Qualification levels for substrate/build-platform adhesion

Level	Evidence package	Permitted statement
A - print retention	Defined print remains attached through the declared build and removal workflow.	Process-specific successful attachment only.
B - comparative adhesion	Matched substrates/treatments tested with one quantitative interface-sensitive method.	Relative ranking within the declared method and state.
C - characterised interface	Comparative test + wetting/surface state + failure location + cure state.	Mechanistically bounded adhesion comparison.
D - durable interface	Level C + relevant solvent/thermal/humidity/UV ageing and retest.	Retained adhesion under the declared conditioning window.
E - application qualification	Level D + application load spectrum, geometry, environment and acceptance criteria.	Application-specific qualification; no transfer beyond the validated envelope.

11. Failure-mode and discrimination matrix

Table 4. Common failure observations and discriminating tests

Observation	Competing explanations	Discriminating evidence
First layer remains on vat	Low substrate adhesion; high vat release force; insufficient interface cure; platform contamination.	Inspect both surfaces; exposure series; platform cleaning/treatment; release-force history; failure location.
Part slides but does not fully detach	Marginal adhesion; high shear component; uneven levelling; local cure heterogeneity.	Platform parallelism; footprint map; orientation/load analysis; interface imaging.
Part breaks during removal from platform	Excessive adhesion; weak green/cohesive strength; stress concentration; overcured base.	Fracture location; base-layer geometry; matched pull-off/shear; cure-state comparison.
Good initial adhesion, poor after solvent wash	Treatment/interlayer instability; polymer swelling; hydrolysis; residual stress release.	Aged vs unaged interface test; mass/dimension change; surface chemistry where justified.
Adhesion varies by substrate lot	Oxide/contamination/roughness variation; treatment age; surface-energy drift.	Surface characterisation and lot-controlled replication.
High pull-off but poor lap shear	Load-mode dependence; brittle interphase; adherend bending/stress concentration.	Matched normal/shear tests and fracture-surface analysis.
Primer improves print success but not aged bond	Primer may improve wetting or early cure without durable coupling.	Initial vs conditioned mechanical testing; primer/substrate failure location.

12. Standards and current evidence gap

No published ISO or ASTM standard identified in this review directly defines build-platform adhesion of a vat-photopolymerised first layer or permanent adhesion of a VPP structure to a functional substrate. ISO 4624:2023 [S1] and ASTM D4541-22 [S2] address pull-off testing of coatings; ISO 4587:2003 [S3] addresses lap-shear of rigid bonded assemblies. They provide useful method architecture but not VPP-specific exposure, first-layer, geometry, platform-motion or vat-release controls.

Consequently, a current VPP adhesion claim should name the adapted standard or in-house method, specimen geometry, substrate preparation, cure state, conditioning, loading rate and failure classification. Results from different methods should not be collapsed into a single universal "adhesion strength" ranking.

13. Scope boundaries within the Engineering Review series

ER-53 is deliberately positioned between several existing reviews without duplicating them:

- ER-34 controls vat-film separation and peel mechanics. ER-53 treats that separation force only as a competing load on the desired substrate interface.
- ER-43 controls interfaces between intentionally different printed materials and functionally graded regions. ER-53 concerns a printed photopolymer bonded to a non-native substrate or build platform.
- ER-73 controls native same-material layer boundaries and mechanical anisotropy. ER-53 excludes same-material successive-layer cohesion.
- ER-31 controls cure shrinkage, residual stress and warpage. ER-53 uses residual stress only where it changes substrate-interface failure.
- ER-27 controls conversion metrology. ER-53 uses conversion as an interfacial state variable, not as an adhesion surrogate.
- ER-41 controls chemical resistance and solvent uptake; ER-72 controls environmental ageing. ER-53 uses those exposures only to assess adhesion retention.
- ER-59 and ER-63 control dual-cure and adaptable-network chemistry. ER-53 does not infer an adhesion benefit from a chemistry label without interface-specific testing.

14. 3Dresyns implementation boundary

Current controlled 3Dresyns documentation contains a coherent implementation family relevant to this review. 3D-ADD AA1 is positioned as a hydrophilic adhesion-promoting additive for difficult surfaces, including metal, glass and engineering plastics. 3D-ADD AA2 Bio is the hydrophobic adhesion-promoter route. 3D-ADD AA3 is positioned as an adhesive and interfacial promoter for difficult surfaces. 3Dresyn AP1 is a build-platform adhesive primer. 3D-ADD AA1, AA2 Bio and AA3 and 3Dresyn AP1 are described in current controlled public technical documentation (TDS revision 1.3, August 2026) [M1-M4].

3D-ADD NSA1, a non-stick additive positioned to reduce release force at FEP/PDMS, is relevant only as the opposite side of the bottom-up force balance [M5]. It is not an adhesion promoter and is not used here as evidence of substrate-bond performance.

These manufacturer sources establish product identity and intended implementation role only. They do not establish universal adhesion strength, compatibility with every resin or substrate, superiority to silanes/primers, service durability, or compliance with ISO 4624, ISO 4587 or ASTM D4541. Any product-specific adhesion claim requires the exact resin/additive version, dosage, substrate, surface preparation, printer/exposure, conditioning and mechanical test.

15. Research and standardisation priorities

- a VPP-specific first-layer adhesion artefact that separates build-platform attachment from vat-interface release;
- a common method for reporting substrate preparation, roughness, contact angle and treatment age;
- interface-targeted specimens that distinguish adhesive from cohesive and primer/interlayer failure;

- correlated conversion, chemistry and stress mapping through the first 100-500 micrometres adjacent to the substrate;
- validated microstructure shear methods for 2PP and micro-VPP structures;
- ageing matrices that compare initial and retained adhesion after solvents, water, heat, UV and humidity;
- interlaboratory studies across glass, stainless steel, aluminium, ITO and representative engineering polymers;
- a reporting convention for the competing adhesion ratio between build-platform retention and vat-interface separation;
- failure criteria for hybrid manufacturing in which VPP structures are printed directly onto functional components;
- distinction between process-retention primers and permanent structural-interface promoters.

16. Conclusions

Substrate and build-platform adhesion in vat photopolymerisation is a coupled interfacial problem, not a scalar resin property. Wetting enables contact but does not establish cured strength. Surface treatments such as plasma activation and silanisation can improve bonding, but their durability depends on chemistry and post-processing. Polymeric interlayers and reactive promoters can create additional coupling routes while also introducing additional interfaces that must be qualified.

The VPP process adds a constraint absent from many conventional adhesive tests: the desired first-layer interface is repeatedly loaded while the opposite vat interface is intentionally detached. Exposure, platform motion, footprint, residual stress and vat release therefore belong in the process record. For permanent substrate printing, the evidence must extend beyond print success to quantitative mechanical testing and ageing.

A defensible adhesion claim should therefore contain: declared substrate state + declared resin/cure state + wetting/surface evidence where relevant + interface-sensitive mechanical test + verified failure location + conditioning history + uncertainty. Until a dedicated VPP adhesion standard exists, this complete record is the appropriate engineering basis for comparison and qualification.

Limitations

This review is a literature-based engineering synthesis and reports no new adhesion experiments. Direct quantitative VPP evidence is strongest for initial DLP build adhesion and for two-photon-polymerised microstructures on glass, silicon, ITO and treated/interlayered substrates. UV-curable coating and adhesive studies are used only as adjacent mechanistic evidence and are not quantitatively transferred to VPP. The 2026 Roig et al. article was available online as an open-access journal pre-proof at the time of drafting; bibliographic metadata should be rechecked after assignment to a final issue. Standards status should likewise be rechecked immediately before public release.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. Manufacturer documentation is included only as implementation context and is separated from independent scientific evidence.

Data availability

No new experimental dataset was generated for this review. Scientific statements derive from the cited literature and standards; manufacturer examples derive from controlled 3Dresyns documentation.

Company information

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Standards

- [S1] ISO 4624:2023, Paints and varnishes - Pull-off test for adhesion. Official record: <https://www.iso.org/standard/83350.html>
[S2] ASTM D4541-22, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers. DOI: <https://doi.org/10.1520/D4541-22>
[S3] ISO 4587:2003, Adhesives - Determination of tensile lap-shear strength of rigid-to-rigid bonded assemblies. Official record: <https://www.iso.org/standard/34852.html>

Manufacturer documentation

- [M1] 3Dresyns, 3D-ADD AA1 Adhesive Additive for adhesion on difficult surfaces, TDS v1.3, August 2026. Product page: <https://www.3dresyns.com/products/3d-add-aa1-adhesive-additive-for-adhesion-on-difficult-surfaces>
[M2] 3Dresyns, 3D-ADD AA2 Bio Hydrophobic Adhesive Additive for adhesion on difficult surfaces, TDS v1.3, August 2026. Product page: <https://www.3dresyns.com/products/3d-add-aa2-bio-hydrophobic-adhesive-additive-for-adhesion-on-difficult-surfaces>
[M3] 3Dresyns, 3D-ADD AA3, Adhesive & Interfacial Promoter for Difficult Surfaces, TDS v1.3, August 2026. Product page: <https://www.3dresyns.com/products/3d-add-aa3-adhesive-interfacial-promoter-for-difficult-surfaces>
[M4] 3Dresyns, 3Dresyn AP1 Adhesive Primer for improving the adhesion on the build platform, controlled TDS, August 2026. Product page: <https://www.3dresyns.com/products/3dresyn-ap1-adhesive-primer-for-improving-the-adhesion-on-the-build-platform>
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