

Environmental Stress Cracking in Printed Photopolymers: Applied Stress, Sorption, Crazeing, Crack Growth and Recovery

A coupled stress-environment framework for screening, diagnosis and bounded qualification

Juan Seguro

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

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Abstract

Environmental stress cracking is a coupled failure process. An environmental agent that produces modest swelling or property drift in an unloaded specimen can accelerate craze initiation or subcritical cracking when tensile stress, residual stress or constraint is present. Conversely, a stressed specimen may survive in air but fail during exposure. Printed photopolymers add orientation, layered defects, wash history, conversion gradients, support scars, surface inhibition and residual stress to this coupling. Unconstrained immersion, ordinary creep and post-exposure strength loss are therefore informative controls but are not, alone, environmental stress cracking tests.

This review defines a non-compensatory qualification framework for printed photopolymers under combined stress and environmental exposure. It separates uptake, plasticisation or antiplasticisation, swelling, crazeing, crack initiation, crack growth and final rupture; distinguishes constant-load, constant-strain and bent-strip methods; and requires stress relaxation, changing geometry and chemical activity to be reported. Mass recovery after desorption does not prove mechanical recovery, while absence of visible cracks does not prove unchanged residual strength. Direct evidence confirms environment-dependent mechanical drift in printed photosensitive polymers, but much mechanistic environmental stress cracking literature concerns thermoplastics. That evidence can guide test logic and diagnostics, not establish quantitative limits for crosslinked vat photopolymers. No universal safe-solvent list, critical stress, exposure time or recovery factor is supported.

Keywords: printed photopolymer; environmental stress cracking; solvent sorption; applied stress; crazeing; crack growth; residual strength; recovery

1. Significance and scope

Printed photopolymer components encounter wash solvents, cleaners, fuels, oils, beverages, disinfectants, humidity and mixed chemicals while carrying assembly, pressure or residual stresses. Failure may occur below the short-term strength measured in air because the environment changes mobility, local cohesion, interfacial behaviour or crack-tip processes.

ER-236 addresses failure created by the coupled action of stress, environment and time. Its purpose is to distinguish reversible sorption effects from irreversible damage and to define evidence needed for a bounded compatibility claim.

1.1 Corpus boundary

ER-010 retains dimensional and geometric metrology. ER-039 retains general creep and long-term mechanical response. ER-041 retains chemical resistance, solvent uptake and recovery without the applied-stress cracking claim. ER-054 retains general diffusion, sorption and permeability. ER-069 retains general crack-growth kinetics. ER-070 retains fracture toughness. ER-072 retains environmental ageing and property retention outside the stress-cracking mechanism. ER-088 retains surface topography, roughness and finishing. ER-170 retains accelerated ageing. ER-171 retains design values and allowables; ER-236 provides no transferable allowable. ER-184 retains generic uncertainty inference. ER-207 retains residual-stress measurement. ER-232 retains notch sensitivity. ER-235 retains general multiaxial failure criteria. ER-236 uses those domains only to identify the coupled stress-environment state.

2. Define environmental stress cracking operationally

An ER-236 claim requires three elements: a defined environmental agent, a defined applied or residual tensile stress, and damage or failure that depends on their coupling. A liquid-immersed but unloaded coupon can establish uptake, swelling and baseline property drift. A loaded coupon in air can establish creep or static rupture. Neither alone demonstrates environmental stress cracking.

The environmental term includes liquid, vapour, humidity or mixtures with stated composition and activity. The stress term includes constant load, constant displacement, bending, residual stress or a measured multiaxial state. The outcome may be craze initiation, crack initiation, crack growth, loss of residual strength or rupture.

3. Freeze the printed and chemical states

Record resin and batch, printer, wavelength and exposure, build location and orientation, layer thickness, supports, wash solvent and duration, drying, post-cure spectrum and temperature, storage, surface finishing and specimen age. Record the environmental agent, grade, water content, concentration, mixture composition, temperature, agitation, renewal and evaporation control.

Orientation and post-cure affect mechanical response in SLA materials [7,8]. Cure time likewise changes strength measured across rate regimes [6]. These are baseline covariates, not direct environmental stress cracking evidence. They must be frozen so exposure effects are not confused with initial-state differences.

4. Measure uptake and dimensional change as covariates

Track mass, dimensions and, where useful, solvent content during exposure and desorption. Report whether values are referenced to the dry initial state, exposed state or recovered state. Use enough time points to distinguish early uptake from an apparent plateau.

The printed-photosensitive-polymer study directly shows that liquid exposure duration and medium can alter flexural response [1]. It supports coupling of exposure history and mechanical state, but its circular-ring geometry and selected liquids do not define universal diffusion coefficients or compatibility limits.

Uptake is not damage. A specimen can absorb liquid without visible cracking, and a small mass change can still alter a crack-tip process. Conversely, swelling can change fixture stress and complicate interpretation.

5. Separate plasticisation, antiplasticisation and damage

An environmental agent may reduce glass-transition temperature or stiffness through increased mobility, increase apparent stiffness in a limited concentration range, extract constituents, cause additional curing, swell interfaces or promote microvoiding. Report modulus, strain at failure, strength and residual properties rather than using one metric as a proxy for all mechanisms.

Reversible softening during exposure should be distinguished from irreversible craze or crack damage. A return of mass or modulus after drying does not prove full recovery of strength, fatigue resistance or fracture behaviour.

6. Choose constant-load, constant-strain or bent-strip control deliberately

Under constant load, specimen strain and crack-tip driving force can evolve as the material softens or the section damages. Under constant displacement, stress may relax during sorption. Bent-strip tests are convenient screens but produce a stress gradient that depends on thickness, radius, modulus and large-deformation assumptions.

Report the control mode, initial stress or strain, compliance, feedback, geometry and the quantity actually held constant. Do not compare time to failure across control modes as if they measured the same threshold. For constant strain fixtures, measure relaxation where practicable. For constant-load tests, track deformation and section change.

7. Control residual stress and surface state

Post-cure gradients, support removal, machining, press fits, fasteners and adhesive shrinkage can provide the tensile stress needed for cracking. Surface scratches, layer boundaries, pixel-scale roughness and inhibited regions can localise initiation. Record whether the test isolates applied stress, residual stress or both.

A stress-free control should share the same surface preparation and exposure. A stressed air control should share the same fixture and duration. If support scars or machined edges are included intentionally, they define a component-relevant surface state rather than an intrinsic material limit.

8. Use an exposure-stress-time matrix

At minimum, include several stress or strain levels, several exposure times, an unloaded exposed control and a loaded unexposed control. Include replicates and randomise position where temperature, evaporation or illumination may vary. For mixtures, control composition throughout the test.

The FDM formwork investigation demonstrates that printed polymers can crack under a chemically aggressive environment and stress, and that material or barrier selection can change performance [2]. It is useful adjacent evidence for coupled-test logic. Its thermoplastic process, alkaline concrete environment and mitigation results are not quantitative evidence for vat-printed photopolymers.

9. Observe craze and crack development independently

Crazes are localised fibrillated or voided zones that can precede cracks in some polymers, but optical whitening is not a universal craze measure. Use microscopy, transmitted light, digital image correlation, acoustic methods or X-ray imaging as appropriate. Define detection resolution and whether observations are surface or volumetric.

HDPE work using interrupted full-notch creep tests distinguishes craze-zone length from actual crack length and shows that a formed craze need not evolve identically under every condition [4]. This is mechanistic-adjacent evidence from a semicrystalline thermoplastic. It supports separate observation of craze and crack, not direct transfer of its stresses, media or kinetics.

10. Quantify initiation, propagation and rupture separately

Time to visible craze, time to first crack, crack-growth history and time to rupture answer different questions. A test censored before rupture can still contain useful initiation data. Report censoring and do not assign the exposure duration as a failure time for intact specimens.

When crack length is measured, state the optical or imaging method, threshold, calibration and uncertainty. If a fracture-mechanics parameter is calculated, verify that geometry, constitutive behaviour and crack-tip assumptions are appropriate. Generic crack-growth analysis remains under ER-069 and toughness under ER-070.

11. Treat stress relaxation and creep as coupled covariates

Environmental uptake can change compliance, so stress in a constant-strain specimen may decrease while local damage grows. Constant-load specimens may creep and change net-section stress. Measure force or displacement histories rather than assuming the initial value persists.

The recent mechano-sorptive synthesis places environmental stress cracking and stress-sorption creep within a coupled framework [3]. It is a review, not primary photopolymer evidence. Its role here is conceptual: stress, sorption and time must be observed together, while quantitative limits must come from the printed material under qualification.

12. Control temperature and chemical activity

Temperature affects diffusion, relaxation, equilibrium uptake and reaction rates. Chemical activity can change when a solvent mixture absorbs water, evaporates or extracts material from the specimen. State temperature stability and composition controls.

Accelerating a test by temperature or concentration can change the governing mechanism. A ranking that remains stable over one accelerated condition is not automatically a service-life model. ER-170 retains general accelerated-ageing design; ER-236 requires mechanism checks specific to the stress-environment coupling.

13. Build a recovery sequence

After exposure, define rinsing, blotting, drying, temperature, humidity and recovery time. Track mass and dimensions until the chosen recovery criterion is met. Then measure residual stiffness, strength or fracture response using matched controls.

Recovery has at least three layers: desorption or mass recovery, dimensional recovery and mechanical recovery. They must not be collapsed into one factor. Ageing experiments on vat-printed elastomeric structures show why post-processing, time and mechanical state require explicit controls [5], but ageing without an aggressive environment is not environmental stress cracking.

14. Distinguish screening from qualification

A bent-strip or fixed-deflection test can rank resin-environment combinations quickly. Qualification requires calibrated stress or strain, state-controlled specimens, replicated outcomes, damage observation and residual-property evidence. Component testing may then address multiaxial stress, joints, seams and realistic surface defects.

Absence of visible cracking in a screen supports only the detection limit and duration used. It does not prove unchanged strength or indefinite compatibility. A safe-solvent list must therefore be replaced by a matrix bounded to resin, print state, surface, stress, activity, temperature and time.

15. Model coupled transport and damage cautiously

A model may link concentration-dependent properties to diffusion and stress, or use empirical time-to-initiation and crack-growth relations. State whether transport is Fickian, concentration-dependent, swelling-coupled or reaction-limited. Use measured uptake and geometry rather than assigning a generic diffusivity.

Calibrate transport and mechanical components separately where possible, then test the coupled prediction. Reserve at least one stress, thickness, exposure level or recovery sequence as a holdout. A model that requires a new damage parameter for every condition describes the dataset but has not demonstrated transfer.

16. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Printed state	Resin, exposure, wash, post-cure, orientation and surface	Pooling unlike baseline states
Environment	Composition, activity, temperature and renewal	Calling a solvent name a condition
Stress	Control mode, history, residual stress and geometry	Treating initial fixture setting as persistent stress
Damage	Separate uptake, craze, crack and rupture observations	Calling swelling environmental stress cracking
Recovery	Mass, dimensions and residual mechanics	Equating desorption with healing
Transfer	Holdout stress, thickness or environment	Declaring universal compatibility

The gates are independent. Stable mass cannot compensate for an unmeasured crack, and a visually intact surface cannot compensate for lost residual strength.

17. Minimum reporting set

Report resin, batch, printer, exposure, orientation, layer, supports, wash, drying, post-cure, storage, specimen age and surface; environment identity, grade, concentration, activity, temperature, agitation, renewal and evaporation control; specimen geometry and as-built dimensions; fixture and stress or strain control; applied and residual stress estimates; force and displacement histories; uptake, swelling and desorption; craze and crack detection method; initiation, propagation, rupture and censoring; recovery sequence; residual properties; replicates, exclusions and uncertainty; model assumptions, calibration and holdout validation; and the exact domain of the claim.

No safe exposure time, critical stress or recovery factor becomes universal when resin, cure, orientation, surface, chemical activity, temperature or load state changes.

18. Knowledge boundary

Direct printed-photopolymer evidence supports environment-dependent mechanical drift [1] and establishes cure, orientation, ageing and baseline state as necessary covariates [5-8]. Direct coupled environmental stress cracking datasets for crosslinked vat-printed photopolymers remain limited. Thermoplastic printed-formwork evidence [2], a mechanistic synthesis [3] and HDPE craze-crack observations [4] support test architecture and diagnostic separation only. They do not establish vat-photopolymer thresholds.

19. Limitations

The evidence spans different chemistries, geometries, liquids and endpoints. Several sources are adjacent rather than direct, and one source is a review rather than primary evidence. Crosslinked photopolymers may craze, crack, swell or soften differently from semicrystalline thermoplastics. Long service periods, mixtures, residual wash solvent and repeated wet-dry cycles remain material-specific. References [1], [2], [4], [5], [6], [7] and [8] were read at full-text depth; reference [3] was used at publisher-abstract depth. This review does not provide a universal solvent ranking or design allowable.

20. Conclusions

Environmental stress cracking of printed photopolymers is a coupled stress-sorption-damage problem. Qualification must include unloaded exposed and loaded unexposed controls, declare constant-load or constant-strain conditions, track relaxation or creep, and separate uptake, crazing, cracking, rupture and recovery. Mass recovery and visual integrity are insufficient proxies for mechanical recovery. Direct printed-photopolymer evidence must control quantitative conclusions, while thermoplastic evidence may guide mechanisms and test logic only. The defensible output is a bounded compatibility envelope for a defined printed state, environment, stress, temperature and time.

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