

Fatigue-Crack Growth and Subcritical Fracture in Vat-Photopolymerised Thermosets: Crack Preparation, Cyclic Driving Force, Environment and Qualification

Juan Seguro

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

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Statement of Significance

An S-N curve, monotonic fracture-toughness value, impact result or high elongation does not establish resistance to the growth of an existing crack under repeated loading. For vat-photopolymerised thermosets, cyclic crack propagation is coupled to crack sharpness, layer orientation, cure state, viscoelastic heating, environment and residual stress. This review defines a crack-controlled qualification architecture and treats the limited direct VPP evidence as an evidence gap rather than filling it by unqualified transfer from bulk polymers, metals or fibre composites.

Keywords: vat photopolymerisation; fatigue crack growth; subcritical fracture; da/dN ; stress-intensity range; load ratio; fatigue threshold; crack preparation; build orientation; post-cure; environmental ageing; qualification

Abstract

Fatigue qualification of vat-photopolymerised thermosets is often reduced to cycles to failure for smooth specimens. That measurement is useful but does not quantify the propagation of a pre-existing crack, the operational threshold below which growth becomes difficult to resolve, or the interaction between cyclic driving force and the printed material state. This review separates unnotched fatigue life, crack initiation, fatigue-crack growth and monotonic instability. It organises the problem around the load ratio R , stress-intensity or energy-release-rate range, maximum-cycle driving force, crack-length measurement, specimen geometry, precrack preparation, build orientation, post-cure, residual stress, temperature, frequency and environment. The literature available for printed photopolymers supports strong process-, orientation- and state-dependence of mechanical response, but direct, standards-complete da/dN datasets for VPP thermosets remain limited. Consequently, metallic-material, bulk-plastic and composite standards are treated as method sources whose scope must be declared, not as automatic validation routes. A minimum reporting matrix and failure-mode table are proposed. The central conclusion is that defect tolerance cannot be inferred from tensile strength, impact resistance, static KIC/GIC, or an S-N curve alone. A defensible claim requires a sharp and documented crack, measured growth under a defined cyclic history, state-resolved conditioning, and an application-specific link between the crack-growth law and the defect population of the printed part.

1. Scope and evidence-selection method

ER-69 addresses cyclic propagation of an existing crack in vat-photopolymerised thermosets. It does not replace smooth-specimen fatigue-life testing, static fracture-toughness measurement, creep or stress-relaxation testing. The evidence set combines direct or adjacent studies on additively manufactured photopolymers, fatigue response, fracture and cure-state dependence [1-18]. Standards are used only within their stated material and test scopes. No value from a metal, fibre composite, bulk-moulded plastic or one proprietary VPP formulation is treated as a universal target for another printed resin.

The review uses three evidence levels: direct VPP evidence, adjacent polymer or additive-manufacturing evidence, and method-source standards. Where direct crack-growth evidence is absent, the gap is stated. Mechanistic plausibility is not upgraded to validation.

2. Fatigue life, crack initiation and crack growth are different measurands

Smooth-specimen fatigue testing reports a life distribution under a declared stress or strain history. That life can include defect nucleation, microcrack coalescence and final propagation. A precracked specimen removes much of the initiation interval and asks a different question: how rapidly does a crack of measured length grow under a defined cyclic driving force? The distinction is central in polymers and additively manufactured materials, where process defects can act as initial cracks or notches [1-7,9-11,15].

Table 1. Mechanical quantities that must not be treated as interchangeable.

Quantity	Primary result	What it does not establish
Smooth-specimen fatigue life	Cycles to a declared failure under stated stress/strain, R , frequency and environment.	A material crack-growth law or threshold.
Impact resistance	Energy absorbed in a high-rate notched or unnotched impact configuration.	da/dN under cyclic loading or static KIC/GIC.
Tensile toughness	Area under a tensile stress-strain curve for a stated specimen and rate.	Resistance to extension of a sharp crack.
Static KIC or GIC	Critical monotonic crack-driving force when validity requirements are met.	Subcritical cyclic growth below monotonic instability.

Quantity	Primary result	What it does not establish
Fatigue-crack-growth rate	da/dN versus ΔK , ΔG or another declared cyclic driving force.	Component life without initial-defect, geometry and load-history information.
Damage tolerance	Structural acceptance based on defects, growth, inspection, residual strength and service history.	A resin-only scalar property.

3. Cyclic crack-driving-force variables

3.1 Load ratio and stress-intensity range

For a nominally linear-elastic Mode I test:

$$R = K_{min} / K_{max} = P_{min} / P_{max}$$

$$\Delta K = K_{max} - K_{min}$$

A reported da/dN- ΔK curve is incomplete without R and Kmax. Two tests at the same ΔK but different R can have different mean stress, crack opening, viscoelastic deformation and proximity to monotonic instability. Negative-R loading also introduces reversal and possible crack-face contact. The full waveform is therefore part of the material state, not an incidental machine setting.

3.2 Energy-release-rate and nonlinear alternatives

When the fracture process zone, viscoelasticity or specimen deformation is too large for a small-scale-yielding interpretation, an energy-based or J-based quantity may be more appropriate. Static fracture studies already show that specimen geometry and validity conditions control whether a reported value is a material parameter or a conditional result [1,2,4-7,9-11,15]. ER-69 therefore requires the selected driving force to be justified rather than chosen only because test software exports it.

3.3 Maximum-cycle condition

Cyclic growth can accelerate because ΔK increases, because Kmax approaches the monotonic resistance of the conditioned specimen, or because time-dependent damage accumulates during the cycle. A growth law that uses only ΔK may conceal a Kmax-controlled transition. Report both quantities, and identify any static hold or dwell segment.

4. Evidence state for VPP thermosets

The reviewed printed-photopolymer literature demonstrates that fatigue response and fracture depend on formulation, cure, build orientation, specimen geometry and post-processing [1-6,8-14,16-18]. Those findings justify treating the printed state as part of the test definition. They do not by themselves provide a transferable fatigue-crack-growth law.

Within the evidence set used here, complete direct datasets combining a sharp fatigue precrack, measured crack length, da/dN, R, frequency, temperature, environment, build orientation and validity screening are sparse. ER-69 therefore functions as a qualification and reporting review, not as a numerical meta-analysis. It does not publish a universal Paris-law coefficient, threshold or allowable flaw size.

Table 2. Evidence ladder for a fatigue-crack-growth claim.

Level	Minimum evidence	Permitted conclusion
0. Descriptor	Tough, impact-resistant, flexible, high-elongation or fatigue-resistant label.	Candidate-selection language only.
1. Smooth fatigue	S-N or strain-life data with full load and conditioning history.	Life of the tested smooth specimen.
2. Notch sensitivity	Matched smooth/notched tests with notch geometry and radius.	Sensitivity to that notch configuration.
3. Measured crack growth	Sharp crack, crack-length metrology and da/dN under declared R/frequency/environment.	Conditional crack-growth response for the tested state.
4. Validated parameter	Geometry, crack and linearity/process-zone validity demonstrated for the chosen parameter.	Material-parameter claim within the validated range.
5. Damage tolerance	Defect distribution, structural stress, growth model, inspection and residual strength linked.	Application-specific defect acceptance and inspection interval.

5. Specimen geometry and crack preparation

An as-printed notch is not automatically a crack. Pixelation, cure broadening, trapped resin, stair stepping and post-cure can produce a finite-radius root whose response is notch-controlled. Static VPP fracture work and the broader plastics-fracture methodology both require explicit crack preparation and dimensional verification [1,2,4-7,9-11,15].

- Report the specimen type, dimensions, thickness, span or load-line geometry, crack plane and loading mode.
- Record the printed notch dimensions, measured root radius and any razor tapping, broaching or cyclic precracking step.

- Demonstrate that the starter crack lies within the intended plane and is not diverted immediately into a support scar, surface-cure layer or unintended interlayer boundary.
- Separate crack-preparation cycles from the data-reduction interval and report the transition criterion.

A fatigue precrack can improve sharpness but can also create a history-dependent process zone. The precracking R ratio, frequency, growth increment and final K_{max} must therefore be retained in the record.

6. Crack-length measurement and compliance calibration

Crack length may be measured optically, by compliance, by potential-drop methods where a conductive path is available, or by validated imaging. Transparent and translucent photopolymers offer optical access but can also produce refraction, subsurface crack fronts and whitening that obscure the true front. Surface crack length should not be assumed equal to the through-thickness average.

- State image scale, illumination, edge-detection rule and temporal sampling.
- If compliance is used, provide the calibration relation and verify it for the printed modulus, specimen geometry and fixture compliance.
- Use post-mortem fracture-surface marking or sectioning where needed to assess crack-front curvature and unintended branching.
- Report the smallest resolvable growth increment before assigning a near-threshold plateau.

7. Loading programme, frequency and waveform

Polymers can exhibit frequency-dependent heating, rate sensitivity, creep during dwell and recovery between cycles. Fatigue data for VPP and adjacent polymer systems therefore cannot be compared solely by nominal stress amplitude [1-3]. The control mode, waveform, frequency, R ratio, maximum load, load-shedding procedure and termination rule must be stated.

A load-shedding sequence used to approach a threshold can change process-zone history. Growth-rate data collected during decreasing and increasing driving force should be identified separately. If crack arrest is claimed, specify the growth-rate resolution, number of cycles observed and whether the specimen was subsequently reloaded to confirm detectability.

8. Build orientation, interlayer direction and crack path

Build orientation is insufficient as a single label. The report should define the layer plane, crack plane, nominal growth direction, loading direction and specimen extraction direction. Printed anisotropy may arise from interlayer cure history, oxygen-affected interfaces, support contact, surface finish, optical nonuniformity or post-cure gradients [1-6,8-14,16-18].

A crack that follows an interlayer path measures a different resistance architecture from one that repeatedly crosses layers. Mixed paths and branching should be documented rather than reduced to one nominal orientation code.

9. Cure state, post-processing and residual stress

The as-printed green state, washed state, post-cured state and aged state are different material states. Conversion, gelation, vitrification, network mobility and residual stress evolve through the workflow [1,8,12-14,16,18]. A post-cure can raise stiffness and static strength while also reducing ductility or changing the crack-tip process zone. Direction of change cannot be inferred from dose alone.

Residual stress can superpose with the applied cycle and alter effective crack opening. Warpage correction or machining does not prove that the internal stress field has been removed. Record post-cure spectrum, irradiance, time, temperature, orientation, support condition, cooling and conditioning delay.

10. Temperature, frequency and environment

Solvent uptake, humidity, water, thermal ageing and other environments can change modulus, swelling, crazing, interfacial adhesion and crack-tip dissipation [1-4]. An environmental exposure must therefore be incorporated into the specimen state and, where relevant, maintained during cycling rather than applied only before the test.

- Measure specimen or chamber temperature during long or high-frequency tests; ambient setpoint alone is insufficient if self-heating occurs.
- State whether samples were tested dry, equilibrated, immersed, re-dried or thermally aged.
- Report mass or dimensional conditioning endpoints when uptake or swelling is material.
- Do not transfer a crack-growth curve between environments without demonstrating equivalence.

11. From da/dN data to a qualification decision

A fitted crack-growth relation is an intermediate model, not a component life by itself. Structural qualification additionally requires an initial flaw distribution, local stress history, geometry correction, residual-strength criterion and inspection capability. Model uncertainty and specimen-to-specimen scatter should be propagated rather than hidden in one best-fit line.

$$N_p = \int(a_i \text{ to } a_c) [1 / (da/dN)] da$$

The integral is conceptual unless the growth relation, geometry function, load history and critical crack size are all defined over the relevant range. Extrapolation below the measured threshold region or beyond the validated instability region should be declared.

12. Proposed reporting descriptors

The following are reporting variables, not new standards or acceptance limits:

$$R = P_{min} / P_{max}$$

$$\Delta K = K_{max} - K_{min}$$

$$v_a = da/dN$$

$$N = N_i + N_p$$

Here N_i is the declared initiation interval under the selected criterion and N_p is the measured or modelled propagation interval. The criterion separating them must be reported. An operational threshold, $\Delta K_{th,op}$, should be accompanied by the growth-rate resolution, load-shedding history, R ratio, frequency, environment and crack-detection method. The subscript op is retained to prevent an instrument- and protocol-dependent threshold from being presented as an absolute material constant.

13. Minimum reporting matrix

Table 3. Minimum evidence architecture for fatigue-crack-growth qualification.

Domain	Minimum record	Required conclusion
Material state	Batch, formulation identity, print orientation, wash, post-cure, conditioning and age.	Defines the tested printed state.
Specimen	Geometry, thickness, dimensions, surface state, crack plane and load direction.	Defines the mechanical boundary problem.
Starter crack	Notch manufacture, root radius, sharpening/prec cracking, final a/W and crack-front check.	Shows that a crack, not only a blunt notch, was tested.
Loading	Control mode, waveform, R, frequency, $K_{max}/\Delta K$ or $G_{max}/\Delta G$, dwell and load shedding.	Defines cyclic driving force and time history.
Metrology	Crack-length method, calibration, resolution, sampling and crack-front validation.	Establishes measured growth.
Environment	Temperature, humidity/medium, equilibration, self-heating and test duration.	Defines environmental and rate state.
Validity	Parameter assumptions, process-zone/linearity checks, excluded data and uncertainty.	Bounds the parameter claim.
Translation	Initial flaw, structural stress, critical size, inspection and residual strength.	Supports a damage-tolerance decision.

14. Failure modes and interpretation errors

Table 4. Common failure modes in cyclic crack-growth studies of VPP thermosets.

Observation	Possible interpretation error	Required response
Long smooth-specimen life	Nucleation life treated as slow crack growth.	Test a measured starter crack.
Low growth from printed notch	Blunt notch or cure-filled root treated as a sharp crack.	Measure radius and use validated sharpening/prec cracking.
Same ΔK , different curves	R, K_{max} , frequency, temperature or environment ignored.	Report and control the full cycle state.
Apparent threshold	Growth below optical resolution or load-shedding history.	Declare resolution and verify by reloading/alternate metrology.
Sudden crack-path change	Interlayer diversion, branching or surface/bulk mismatch.	Map the crack front and fracture surface.
Higher post-cure stiffness	Assumed improvement in crack-growth resistance.	Measure da/dN and static instability in the same state.
Orientation label only	Crack plane and growth direction undefined.	Use a complete layer-crack-load coordinate description.
One best-fit Paris line	Near-threshold and instability regimes pooled.	Report fitted range, scatter and excluded regimes.
Fatigue curve used for component life	Initial flaw and inspection omitted.	Perform geometry- and defect-specific life integration.

15. Scope boundaries within the Engineering Review series

- ER-39 addresses smooth-specimen fatigue and time-dependent deformation. ER-69 begins with an existing crack and resolves propagation rate.
- ER-70 addresses monotonic fracture toughness and damage tolerance. ER-69 addresses subcritical cyclic extension below final instability.

- ER-31 addresses shrinkage, residual stress and warpage. ER-69 treats residual stress only as a contributor to effective cyclic crack driving force.
- ER-41 addresses chemical resistance and solvent uptake. ER-69 uses environmental conditioning only where it changes cyclic crack growth.
- ER-61 addresses gelation, vitrification and mobility arrest during cure. ER-69 requires the resulting cure state to be fixed and reported before cycling.
- ER-67 addresses hierarchical and double-network hydrogels in the hydrated state. ER-69 is restricted to thermoset crack-growth qualification and does not define hydrogel tearing or cyclic-dissipation methods.

16. 3Dresyns implementation boundary

ER-69 does not identify any standard 3Dresyns product as independently validated for fatigue-crack-growth rate, fatigue threshold or defect-tolerant service life. Product or marketing descriptors such as tough, impact-resistant, flexible, foldable, engineering, durable or fatigue-resistant must not be converted into da/dN, $\Delta K_{th,op}$ or inspection-interval claims without crack-controlled testing of the exact printed and conditioned state [M1].

A development or selection workflow may use tensile, impact and smooth-fatigue data for screening. Release-grade qualification additionally requires the crack, load, orientation, post-cure, environment and validity controls defined in this review. Printer compatibility and exposure calibration remain formulation- and machine-specific.

17. Design rules

- Separate crack initiation life from crack propagation life.
- Use a measured sharp crack; do not rename a printed notch as a fatigue precrack.
- Report R, K_{max}, ΔK or the justified energy-based equivalents together.
- Define layer plane, crack plane, growth direction and load direction.
- Control temperature, frequency, waveform, dwell and environment.
- Treat washing, post-cure, conditioning and ageing as part of the material state.
- Declare the measured growth-rate range and do not extrapolate a threshold without resolution evidence.
- Link any component-life claim to initial flaws, structural stress, residual strength and inspection.

18. Limitations

This review does not provide a universal Paris-law coefficient, fatigue threshold, critical flaw size or inspection interval. The selected literature spans different photopolymers, additive-manufacturing processes, specimen geometries and conditioning states. Quantitative values are not pooled across those states. Reference [15] remained online ahead of print when rechecked on 25 August 2026; volume, issue and pagination must be reconfirmed immediately before deposit.

ISO 15850 provides a plastics-specific tension-tension fatigue-crack-propagation route, while ASTM E647 is a widely used crack-growth method and ASTM D7791 and ISO 13003 address different fatigue scopes. None is asserted here as a complete VPP-specific qualification standard. Applicability, edition and validity requirements must be checked immediately before release and for the intended material and claim.

19. Conclusions

- Fatigue life and fatigue-crack-growth resistance are different engineering quantities.
- A crack-growth claim requires a sharp, documented and measured crack.
- The cyclic driving force is defined by more than amplitude: R, K_{max}, waveform, frequency, temperature and environment matter.
- VPP build orientation must be expressed as a layer-crack-load coordinate relationship.
- Post-cure, residual stress and conditioning are part of the tested material state.
- A da/dN curve becomes a damage-tolerance decision only after it is linked to flaws, structure, residual strength and inspection.

The central engineering principle is: a printed thermoset is not defect tolerant because it is tough, strong or fatigue resistant in a smooth specimen; defect tolerance must be demonstrated through crack-controlled growth and structural qualification.

Declarations

Author contributions: Juan Segurola: 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 material categories are presented only as implementation context. No current product is presented as independently validated for fatigue-crack-growth performance.

Data availability: No new experimental dataset was generated for this review.

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Manufacturer-controlled implementation source

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