

Thermal-Cycling Durability of Printed Photopolymers and Hybrid Assemblies: Expansion Mismatch, Interface Damage and Property Drift

A state-resolved qualification framework for repeated temperature excursions

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Abstract

Thermal cycling is not equivalent to storage at one elevated temperature. Each excursion changes modulus, thermal strain, moisture state and residual stress; repeated reversals can accumulate interfacial slip, crazing, microcracking, warpage and loss of preload even when neither temperature extreme causes immediate failure. Printed photopolymers add cure gradients, orientation, layer structure and post-processing history to this problem. Hybrid assemblies add coefficient-of-thermal-expansion mismatch among resin, fillers, coatings, inserts, adhesives and fasteners.

This review establishes a non-compensatory framework for thermal-cycling qualification. It requires the real part temperature and dwell history, not chamber setpoints alone; separates irreversible post-cure or physical ageing from reversible temperature response; treats ramps, dwells and transitions as independent stressors; and links dimensional, mechanical, thermal and interfacial measurements to a declared service claim. A single glass-transition temperature, heat-deflection temperature or successful visual inspection cannot release a cycling claim. Qualification requires state-matched controls, intermediate inspections, failure-mode attribution, residual-property measurements and a prospective holdout profile. Published photopolymer evidence supports strong temperature and post-cure dependence, but direct, generalisable thermal-cycle datasets remain limited. The defensible output is therefore an application-bounded durability envelope, not a universal number of cycles.

Keywords: printed photopolymer; thermal cycling; coefficient of thermal expansion; residual stress; interface damage; post-cure; warpage; durability qualification

1. Significance and scope

Printed photopolymer components are used beside metals, glass, ceramics, elastomers and other polymers. Temperature changes generate free thermal strain, but constraints convert strain mismatch into stress. The risk is governed by the full assembly, not by the resin alone.

ER-237 addresses repeated temperature excursions of printed photopolymers and hybrid assemblies. It covers dimensional drift, property evolution, interfacial damage and loss of function.

1.1 Corpus boundary

ER-010 retains dimensional and geometric metrology. ER-039 retains general fatigue and creep. ER-070 retains fracture toughness. ER-072 retains environmental ageing outside repeated thermal-mismatch loading. ER-073 retains anisotropy. ER-088 retains surface topography and finishing. ER-170 retains general accelerated-ageing factors and life-claim validity. ER-171 retains design values and allowables; ER-237 provides no transferable allowable. ER-184 retains uncertainty. ER-207 retains residual-stress measurement. ER-235 retains multiaxial failure. ER-236 retains stress-environment cracking. ER-238 retains vibration qualification. ER-237 owns assembly-interface damage only where repeated temperature excursions and expansion mismatch create the driving history.

2. Define the claim and failure event

Declare the service temperature range, number of cycles, ramps, dwells, atmosphere, humidity or immersion state, mechanical constraint and allowable function loss. Distinguish survival, dimensional stability, optical stability, seal retention, electrical continuity, adhesion, stiffness retention and residual strength. These are different claims.

A part can remain intact while its dimensions, modulus, preload or optical transmission drift beyond tolerance. Conversely, a visible colour change need not establish structural failure. Acceptance limits must therefore be endpoint-specific and fixed before testing.

3. Freeze the printed material state

Record resin and lot, printer, wavelength, exposure, build location and orientation, layer thickness, support history, wash, drying, post-cure spectrum and temperature, storage, conditioning and specimen age. Temperature-dependent stiffness and creep of commercial photopolymers can change substantially with thermal treatment [1]. High-temperature storage can also continue chemical and mechanical evolution in a printed resin [2].

Do not treat the initial cycle automatically as damage. It may complete cure, remove absorbed water, relax residual stress or advance physical ageing. A stabilisation phase may be useful, but it must be declared and separated from qualification cycles.

4. Measure the part temperature, not only the chamber

Thermal lag depends on thickness, geometry, conductivity, airflow, contact and fixture mass. Place calibrated sensors at representative hot, cold and slow-response locations. Record chamber air and part temperatures continuously. Start dwell timing only after the defined part locations meet the temperature tolerance.

The temperature difference through a part or across an interface can create transient stress even when the final dwell is benign. Ramp rate is therefore a test variable, not administrative detail.

5. Quantify expansion mismatch and constraint

For a uniform temperature change, the free strain of constituent i is approximately

$$\varepsilon_{th,i} = \alpha_i \Delta T$$

where α_i is the relevant coefficient of thermal expansion and ΔT is the temperature change. In a constrained assembly, the mismatch ($\alpha_1 - \alpha_2$) ΔT contributes to interfacial shear and normal stresses. The actual stress also depends on modulus, geometry, viscoelastic relaxation, cure shrinkage and boundary conditions.

Measure expansion in relevant printed directions and temperature intervals. A single scalar coefficient can conceal anisotropy or a change across the glass transition. ASTM E831 and ISO 11359-2 provide measurement frameworks [6,7]. Specimen preparation and printed axes remain application-specific to the qualification described here.

6. Separate temperature extremes, ramps and dwells

The high dwell can drive post-cure, oxidation, relaxation and creep. The low dwell can increase brittleness and reduce stress relaxation. Fast transitions amplify gradients, while slow transitions allow more viscoelastic redistribution. Equal temperature extrema with different ramp and dwell schedules are not equivalent histories.

Report the complete time-temperature trace and cycle definition. If humidity changes with temperature, control or measure water activity and condensation. Otherwise a nominal thermal test becomes an uncontrolled hygrothermal test.

7. Resolve reversible and irreversible changes

Measure selected properties at the same reference temperature before cycling and after defined cycle blocks. This separates temporary softening at high temperature from permanent property drift. Dynamic mechanical analysis can map storage modulus and damping over temperature, while differential scanning calorimetry can identify transitions or continuing reactions. Neither measurement alone proves service durability.

Orientation-sensitive mechanical response and post-cure effects reported for vat-printed photopolymers [3,4] require matched controls. Changes in strength should not be attributed to cycling unless specimen state, conditioning and test rate are controlled.

8. Design the specimen and assembly hierarchy

Use a hierarchy of neat-resin coupons, printed-feature specimens, representative joints and complete assemblies. Coupons isolate material evolution; joints reveal mismatch and adhesion; assemblies reveal load paths and functional consequences. Passing one level does not automatically qualify the next.

For inserts and bonded joints, record material, surface treatment, roughness, adhesive thickness, cure, edge geometry and preload. Include resin-only and interface-free controls where practical. Sectioning and microscopy should distinguish cohesive resin damage, adhesive failure, interfacial debonding and substrate failure.

9. Control fixture-induced stress

A rigid fixture can create a more severe constraint than service, while a compliant fixture can hide service stress. Define support points, tightening torque, contact materials and thermal expansion of the fixture. Verify that grips do not shield or overconstrain the critical region.

Fasteners require preload monitoring because polymer relaxation and differential expansion can change clamp force. A retained bolt torque after cooling does not by itself establish retained interface pressure during the hot dwell.

10. Use intermediate inspections and residual properties

Inspect at logarithmic or risk-informed cycle counts rather than only at the end. Track mass, dimensions, warpage, crack population, interface displacement and relevant function. Non-destructive imaging can guide destructive sectioning, but resolution and detection limits must be reported.

After cycling, measure residual tensile, flexural, shear or fracture properties as required by the claim. Compare with uncycled specimens aged for the same calendar time and handled identically. Thermal-cycling studies of printed parts show that dimensional effects depend on material and process [5]; such results cannot be transferred as universal correction factors.

11. Avoid a cycle-count-only conclusion

The number of cycles is meaningless without extrema, ramps, dwells, gradients, environment, constraint and failure definition. Cycle acceleration must preserve the dominant mechanism. Raising temperature, steepening ramps or eliminating recovery dwells can activate a different mechanism rather than accelerate the intended one.

Use acceleration only after demonstrating mechanism equivalence through comparable morphology, property evolution and model response. An Arrhenius extrapolation is unsuitable when the dominant process changes across a transition or when mechanical mismatch controls failure.

12. Model only what the measurements identify

Thermomechanical finite-element analysis can map gradients and mismatch stresses, but it requires temperature-dependent modulus, expansion, viscoelastic behaviour, geometry and interface conditions. Validate thermal predictions before interpreting stress. Do not tune uncertain interface parameters solely to reproduce the observed final crack.

Sensitivity analysis should identify whether uncertainty in expansion, modulus, contact or heat transfer controls the prediction. A precise stress field derived from unverified properties is false precision.

13. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Material state	Print, wash, post-cure, age and conditioning	Pooling unlike networks
Thermal history	Measured part temperatures, ramps and dwells	Treating chamber setpoint as exposure
Constraint	Assembly, fixture, preload and interfaces	Calling fixture stress material damage
Mechanism	Location, morphology and intermediate evolution	Counting every visible change as one failure
Residual performance	Reference-temperature properties and function	Equating intact appearance with retention
Transfer	Holdout profile and bounded service domain	Universal cycle-life claim

The gates are independent. A stable modulus cannot compensate for debonding, and a visually intact joint cannot compensate for unacceptable preload loss.

14. Minimum reporting set

Report resin, batch, printer, exposure, orientation, layer, wash, post-cure, age and conditioning; constituent and interface identities; specimen and assembly geometry; expansion and temperature-dependent properties; chamber and part sensor locations and calibration; atmosphere and humidity; thermal extrema, ramps, dwells, gradients and cycle count; fixture and preload; intermediate inspection schedule; dimensional, mechanical, optical or functional endpoints; exclusions and detection limits; uncycled controls; residual properties; failure location and morphology; uncertainty; acceptance limits; and the exact transfer domain.

15. Knowledge boundary

Available evidence demonstrates strong temperature, cure, orientation and ageing dependence in particular photopolymers [1-4]. An adjacent fused-deposition ABS study demonstrates process-specific dimensional effects under thermal cycling [5]. Standards support measurement of expansion and thermomechanical response [6-8]. Direct replicated evidence covering broad vat-photopolymer families, realistic hybrid assemblies and long thermal-cycle histories remains sparse. This review therefore releases a qualification architecture, not universal endurance values.

16. Limitations

Published studies use different printing technologies, commercial formulations, thermal histories and endpoints. Some evidence concerns material jetting, tooling or fused-deposition ABS rather than neat vat-printed coupons. Proprietary resin composition and transition structure are often incompletely disclosed. References [1-5] were read at full-text depth; references [6-8] were verified at bibliographic-record depth. No universal acceleration factor, temperature range, cycle count or retained-property threshold is supplied.

17. Conclusions

Thermal-cycling durability is an assembly- and state-resolved problem. Qualification must measure the real part history, separate irreversible evolution from reversible response, quantify expansion mismatch and constraint, inspect intermediate damage and verify residual performance at a common reference state. Transfer requires mechanism equivalence and a prospective holdout profile. The defensible result is a bounded durability envelope for a defined printed material and assembly, not a generic number of cycles.

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