

Heat Generation and Dissipation During Vat Photopolymerisation: Reaction Kinetics, Geometry, Transport and Hot Spots

Separating chemical heat release from transport limits so that temperature becomes a measurable process-state variable

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Abstract

Temperature during vat photopolymerisation is not merely a boundary condition: it is generated by reaction, redistributed by conduction and heat transfer, and fed back into conversion kinetics and viscosity. This review treats that thermal history as a process-state variable. It relates volumetric heat release to conversion rate, conductive relaxation to feature scale, and boundary sensitivity to the window, platform and vat. Surface thermography, embedded temperature sensing and conversion-resolved calorimetry are combined so that optical non-uniformity can be separated from thermal accumulation. Projected-area, thickness, dwell and vat-temperature perturbations then define where a thermal profile can be transferred across geometry and where duty-cycle or compensation limits must be imposed.

Keywords: vat photopolymerisation; reaction exotherm; thermal transport; hot spots; degree of conversion; thermal monitoring

1. Qualification problem: thermal cure state

Qualification of thermal cure state turns on whether the measured state remains transferable when geometry or duty changes. The review therefore connects whether a profile is thermally transferable across part size, maximum projected area or duty cycle before thermal accumulation becomes material, and whether exposure compensation should target optics or temperature to thermal Fourier number Fo , reaction-to-diffusion timescale ratio, and Biot-type boundary sensitivity rather than to nominal machine settings alone. [3,4]

1.1 Scope boundary.

ER-351 owns reaction heat generation and heat rejection during cure. ER-352 owns reaction-diffusion fronts, ER-353 buoyancy-driven transport, ER-354 shrinkage-driven flow, and ER-360 multiphysics verification and validation; those mechanisms are invoked here only where they alter the thermal state or its qualification.

2. Governing balances for thermal cure state

The thermal model is anchored by the three relations below, which separate heat generation, heat transport, and relaxation time.

$$q''' = \rho_r \cdot \Delta H_p \cdot d(\alpha)/dt \text{ couples conversion rate to volumetric heat generation}$$

$$\rho c_p dT/dt = \text{div}(k \text{ grad } T) + q''' + q_{\text{abs}} \text{ separates reaction and optical heat sources}$$

$$t_d \sim L^2/\alpha_{\text{th}} \text{ sets the conductive relaxation time over thermal length } L$$

These coordinates are kept separate because thermal accumulation can change even when nominal exposure is unchanged.

3. Regime boundaries for thermal cure state

Table 1 is used to decide when a thermal result may be transferred to another geometry or duty cycle; it is not a second statement of the equations.

Table 1. Regime indicators for thermal state.

Indicator	Engineering meaning	Use
thermal Fourier number Fo	$\alpha_{\text{th}} t/L^2$, comparing process time with conductive relaxation	For the decision 'whether a profile is thermally transferable across part size', use thermal Fourier number Fo as the transfer boundary because it expresses $\alpha_{\text{th}} t/L^2$, comparing process time with conductive relaxation.
reaction-to-diffusion timescale ratio	cure time relative to thermal relaxation	For the decision 'maximum projected area or duty cycle before thermal accumulation becomes material', use reaction-to-diffusion timescale ratio as the transfer boundary because it expresses cure time relative to thermal relaxation.
Biot-type boundary sensitivity	degree to which window/platform heat transfer controls cooling	For the decision 'whether exposure compensation should target optics or temperature', use Biot-type boundary sensitivity as the transfer boundary because it expresses degree to which window/platform heat transfer controls cooling.

A transfer claim is limited to combinations represented by the test matrix; unvisited thermal regimes remain outside the qualified envelope.

4. Couplings that move the thermal cure state

Temperature accelerates radical kinetics and changes viscosity, so the source term and transport properties co-evolve.

Projected area, layer stack and inter-layer dwell determine thermal accumulation. [3,4]

Window, platform and vat temperature define non-adiabatic boundary conditions.

5. Failure signatures and false diagnoses

Failure attribution is built around localised overconversion and property gradients, thermal broadening of cured geometry and residual-stress amplification after differential cooling. The measurement trio surface IR thermography synchronised to exposure, embedded micro-thermocouples or thin-film sensors for subsurface histories and photo-DSC/DSC enthalpy with conversion measurements separates these branches so that an endpoint shift is not mistaken for a mechanism. The four Table 2 rows are read as causal contrasts: a retained diagnosis must follow its own intervention while the other signatures remain bounded.

Table 2. Failure-mode discrimination for thermal state.

Failure mode	Observable signature	Discriminating evidence
localised overconversion and property gradients	surface IR thermography synchronised to exposure	vary projected area at fixed radiant exposure
thermal broadening of cured geometry	embedded micro-thermocouples or thin-film sensors for subsurface histories	vary feature thickness and inter-layer dwell independently
residual-stress amplification after differential cooling	photo-DSC/DSC enthalpy with conversion measurements	repeat identical exposure histories at controlled vat temperatures
apparent exposure non-uniformity caused by thermal rather than optical variation	geometry-resolved temperature fields and cooling curves	measure conversion and temperature together to separate hotter cure from slower heat rejection

6. Measuring thermal cure state with traceable uncertainty

Traceable measurement uses the three Table 2 channels as separate coordinates. Calibration, spatial registration and repeatability are documented for each before their uncertainties are combined at the decision level. Evidence for thermal cure state is not accepted from a single nominal condition; during metrology of thermal cure state, thermal boundary conditions is resolved against conversion-viscosity feedback. The analysis requires independent resolution of reaction heat release and conductive relaxation, follows it with separate monitoring of conversion-viscosity feedback, and uses an uncertainty-controlled perturbation of thermal boundary conditions as a targeted challenge wherever the two indicate different mechanism or margin; the uncertainty record for thermal cure state keeps conversion-viscosity feedback separate from reaction heat release.

7. Experiments that discriminate competing mechanisms

A boundary challenge involving conductive relaxation is the first stress test for thermal cure state; only after that result is bounded is a causal contrast between reaction heat release and thermal boundary conditions interpreted; during the causal challenge for thermal cure state, conversion-viscosity feedback is tested against reaction heat release. The record keeps a replicate test of conversion-viscosity feedback outside that inference and reports it as an independent line of evidence; the experiment for thermal cure state separates reaction heat release from conductive relaxation.

8. Model identification and validation for thermal cure state

[1] [6,7] [2,5] Uncertainty is carried to each Table 3 limit separately; a nominal machine setting is never used as a surrogate for that propagation. Qualification of thermal cure state treats parameter estimation for reaction heat release and conductive relaxation as one axis and an uncertainty-bounded check on conversion-viscosity feedback as another; within model identification for thermal cure state, reaction heat release is not fitted through conductive relaxation. Between them, prediction against thermal boundary conditions supplies the deliberate challenge that determines whether the apparent transfer is mechanistic or merely coincidental; prediction for thermal cure state keeps conductive relaxation independent of thermal boundary conditions.

9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for thermal state.

Decision	Minimum evidence	Acceptance logic
whether a profile is thermally transferable across part size	Evidence must include calibrated surface IR thermography synchronised to exposure in reference and candidate states, with replicate measurements that resolve the margin for whether a profile is thermally transferable across part size.	Accept only if 'vary projected area at fixed radiant exposure' leaves surface IR thermography synchronised to exposure inside the qualified response band and no localised overconversion and property gradients signature appears.
maximum projected area or duty cycle before thermal accumulation becomes material	Demonstrate maximum projected area or duty cycle before thermal accumulation becomes material using paired embedded micro-thermocouples or thin-film sensors for subsurface histories records from the baseline and transfer cases, together with an uncertainty estimate and repeat series.	Retain the decision only where 'vary feature thickness and inter-layer dwell independently' produces the expected bounded change in embedded micro-thermocouples or thin-film sensors for subsurface histories; evidence of thermal broadening of cured geometry rejects the transfer.
whether exposure compensation should target optics or temperature	For whether exposure compensation should target optics or temperature, acquire photo-DSC/DSC enthalpy with conversion measurements at several states bracketing the proposed limit rather than at one nominal condition.	The decision is supported if 'repeat identical exposure histories at controlled vat temperatures' changes photo-DSC/DSC enthalpy with conversion measurements in the validated direction without activating residual-stress amplification after differential cooling; otherwise requalification is required.

The thermal cure state workflow deliberately separates a separate boundary for thermal boundary conditions from tested ranges in reaction heat release and conductive relaxation; this avoids fitting the challenge into the quantity being qualified; inside the thermal cure state envelope, conductive relaxation and thermal boundary conditions define different transfer limits. An explicit transfer limit on conversion-viscosity feedback is then examined on its own terms before any transfer statement is retained; qualification of thermal cure state bounds thermal boundary conditions separately from conversion-viscosity feedback.

10. Design consequences for thermal cure state

A design change is evaluated through a design change governed by reaction heat release, while whether a profile is thermally transferable across part size is controlled independently; an implementation check on thermal boundary conditions then determines whether the implementation remains inside the qualified mechanism; during design implementation for thermal cure state, thermal boundary conditions is constrained by conversion-viscosity feedback. This prevents a nominally unchanged machine setting from masking a different thermal cure state regime; the thermal cure state design record separates conversion-viscosity feedback from reaction heat release.

11. Evidence gaps for thermal cure state

The working sequence for thermal cure state has three parts: scale transfer of reaction heat release; uncertainty in conductive relaxation versus thermal boundary conditions; and independent replication of conversion-viscosity feedback; for unresolved thermal cure state transfer, conversion-viscosity feedback is studied separately from reaction heat release. Each part answers a different engineering question, so uncertainty or failure in one part is not repaired by a favourable result in another; the evidence gap in thermal cure state distinguishes reaction heat release from conductive relaxation.

12. Qualification outcome for thermal cure state

Qualification is defensible only where all three Table 3 rows are supported by their evidence bands. Extrapolation beyond any one boundary requires new validation. Three independent checks structure the thermal cure state assessment; at final qualification of thermal cure state, reaction heat release is reconciled with conductive relaxation. Agreement between measurement and prediction for reaction heat release establishes the primary state, a renewed-evidence trigger when conversion-viscosity feedback changes tests whether that state survives transfer, and causal evidence that separates conductive relaxation from thermal boundary conditions is the perturbation used when the two disagree; the closing thermal cure state claim keeps conductive relaxation distinct from thermal boundary conditions.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No comparative product recommendation is made.

Data availability

No new experimental dataset was generated for this review.