

Recoating Dynamics of Low-Viscosity Photoresins: Meniscus Motion, Settling, Bubble Entrainment and Layer Uniformity

A fluid-state framework for layer replenishment and exposure readiness

Juan Seguro

3Dresyns by Resyner Technologies S.L.

© 2026 Juan Seguro. All Rights Reserved.

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

ER-244 · Engineering Review · Version 0.2 · 21 September 2026

Abstract

Layer exposure in vat photopolymerisation assumes that liquid resin has replenished the target gap and reached an acceptable fluid state. That assumption fails when blade motion, platform travel, cavity geometry, wetting, viscosity, surface tension or entrained gas create a nonuniform layer. “Settling time” is often used ambiguously for free-surface relaxation, squeeze-flow equilibration, bubble escape and particle sedimentation. These processes have different timescales and acceptance variables.

This review defines a qualification framework for recoating and refill of low-viscosity photoresins. It separates bulk refill, meniscus and contact-line motion, residual free-surface waves, local thickness error, bubble entrainment and dispersed-phase sedimentation. Rheology is measured at process-relevant temperature and shear history. Exposure readiness is defined by a measured layer-thickness or interface-stability tolerance rather than a fixed generic delay. Coupons and sensors challenge cavities, islands, area fraction, travel direction and repeated layers. The framework treats blade, gravity, constrained-gap and vacuum-assisted methods as different boundary conditions. No universal viscosity ceiling, lift speed, wait time, bubble-rest period or Stokes correction is supported. The defensible result is a bounded refill and layer-uniformity window for a declared resin, geometry, machine and cycle.

Keywords: vat photopolymerisation; recoating; resin refill; meniscus; layer uniformity; bubble entrainment; free-surface settling; rheology

1. Significance and scope

A resin can cure correctly in a static test and still fail during repeated layer formation. Incomplete refill produces dry or thin regions; free-surface motion changes optical path and layer height; a blade can leave a leading-edge bulge; bubbles can create voids; and low-viscosity pigmented or filled resins can lose compositional uniformity during long builds.

ER-244 owns per-layer fluid replenishment, meniscus motion, exposure-readiness settling, bubble entrainment and layer uniformity for low-viscosity photoresins.

1.1 Corpus boundary

ER-030 retains oxygen inhibition and free-surface cure; ER-035 retains critical exposure and cure-depth interpretation; ER-036 retains rheology, recoating and dispersion of highly filled suspensions; ER-071 retains closed-loop process control; ER-174 and ER-203 retain optical and radiometric state; ER-211 and ER-212 retain formulation-driven viscosity; ER-245 retains vat and feed temperature control; ER-246 retains global resin level, hydrostatic pressure and free-surface drift; ER-248 retains top-down architecture, supports and scale-up; ER-355 retains acoustic and vibration fields; and ER-444 retains microgravity transport. ER-244 treats architecture and formulation as declared boundary conditions and owns readiness of the next liquid layer.

2. Define “settling” unambiguously

Use separate terms:

1. **refill time:** liquid reaches and fills the intended gap;
2. **free-surface relaxation:** waves and meniscus deviations decay within tolerance;
3. **squeeze-flow equilibration:** pressure and thickness in a constrained gap stabilise;
4. **bubble residence or escape:** gas inclusions move, dissolve or remain trapped;
5. **particle sedimentation:** a dispersed solid or pigment migrates under body force.

One timer cannot prove all five. State the measured variable and threshold used to declare exposure readiness.

3. Freeze the layer-formation architecture

Record top-down or bottom-up arrangement, free or constrained surface, blade or roller, vat window, membrane, build-platform motion, gap trajectory, sweep direction, travel distance, rest sequence and nominal layer thickness. The same resin experiences different pressure, shear and contact-line histories in different machines.

ER-248 owns the complete top-down architecture. ER-244 uses that architecture only to define the fluid-mechanical test domain.

4. Measure rheology at process conditions

Report temperature, shear-rate range, pre-shear, rest time, ramp direction, repeatability and whether the liquid is Newtonian, shear-thinning, thixotropic or weakly yield-stress-bearing. A single viscosity value without shear and temperature is insufficient.

The Reynolds study showed how particle fraction and size distribution alter photopolymer-mixture rheology [7]. Its filled systems do not define low-viscosity limits, but they demonstrate why composition and shear history must be declared.

5. Use dimensionless groups as similarity checks

For a characteristic recoating speed U , length L , density ρ , viscosity μ , surface tension γ and gravity g , useful screening groups include:

$$Re = \rho U L / \mu ; Ca = \mu U / \gamma ; Bo = \rho g L^2 / \gamma$$

where Re compares inertia with viscosity, Ca compares viscous with capillary effects, and Bo compares gravity with capillarity. These groups help organise regimes but do not replace geometry-specific validation. Contact angle, wetting hysteresis and confinement introduce additional state.

6. Characterise bulk refill and trapped volumes

Challenge broad areas, narrow channels, cavities, upward-facing concavities, islands and abrupt height transitions. Pham and Ji demonstrated experimentally that recoating over trapped volumes can produce incorrect layer thickness and long waiting periods [1]. Record whether flow reaches every region and whether pressure or air is trapped.

Use transparent surrogates, high-speed imaging, interface sensors or thickness measurements where justified. A successful final part does not identify the refill margin.

7. Resolve meniscus and contact-line motion

Meniscus shape depends on surface tension, wetting, speed, wall geometry and contamination. Measure dynamic rather than only equilibrium contact behaviour when the contact line moves during each cycle. Observe wall climb, pinning, dewetting and direction dependence.

Do not infer the resin-plane height from the bulk vat level when local menisci or cavities dominate.

8. Measure free-surface relaxation directly

Define a tolerance band for local height, slope or ripple amplitude and measure the time to remain inside it. Moghadasi, Mollah, Marla, Saffari and Spangenberg modelled top-down interface stability as a function of viscosity and platform motion [4]. Their stability times are specific to their simulated geometry and acceptance criterion.

Validate sensors against an independent thickness or surface measurement. A fixed delay is acceptable only when supported across the declared state space.

9. Control leading-edge bulge and topographic memory

A blade crossing a deep-to-shallow transition can leave resin excess at the leading edge. Kozhevnikov, Kunnen, van Baars and Clercx combined simulation and experiment to analyse recoating flow [2] and later evaluated blade trajectories that reduce the bulge [3]. These results support topography-resolved testing, not transfer of one blade protocol.

Map thickness error before and after representative transitions, in both sweep directions and over repeated cycles.

10. Distinguish layer-thickness error from cure-depth error

An unexpectedly thick cured layer can result from excess liquid height, optical penetration or both. Measure the liquid layer or interface before exposure where possible, then measure the green cured geometry. Do not tune exposure to hide a recoating defect.

ER-035 retains cure-depth interpretation. ER-244 supplies the fluid-state boundary needed for that interpretation.

11. Identify bubble sources and fates

Bubbles can enter during pouring, mixing, pumping, refill, blade passage, platform motion, separation, leakage or outgassing. Record size distribution, location, residence time and whether bubbles rise, dissolve, migrate to a contact line or become trapped in the exposure zone.

The Lee study compared blade and vacuum recoating and linked bubble control to internal quality in its system [5]. That evidence supports explicit gas control, not a universal requirement for vacuum recoating.

12. Separate mixing from degassing

Mixing can restore compositional uniformity while introducing gas. A rest period can release bubbles while allowing pigments or particles to sediment. Qualify the complete sequence, including mixing intensity, transfer, filtration, vacuum or rest, and time to first exposure.

Use controls that distinguish gas voids, incomplete refill and cured debris. Similar void morphology can arise from different mechanisms.

13. Treat particle sedimentation as a second clock

Even a low bulk viscosity may contain pigments, opacifiers or functional particles. For an isolated spherical particle in a Newtonian liquid at low particle Reynolds number, a screening estimate is

$$v_s = \Delta \rho g d^2 / (18 \mu)$$

where v_s is terminal settling speed, $\Delta \rho$ is particle-fluid density difference and d is particle diameter. Concentration and non-Stokes effects can invalidate this estimate.

Measure actual stability over the longest build and idle period. ER-036 owns highly filled suspension design; ER-244 only checks whether low-viscosity layer formation remains compositionally uniform.

14. Evaluate blade, gravity and vacuum boundary conditions

Record blade gap, profile, compliance, wetting, speed and trajectory where a blade is used. For gravity refill, record platform motion and available flow path. For vacuum-assisted approaches, record pressure history and gas-release evidence.

Method comparisons must use matched resin, geometry, exposure and post-processing. The Lee comparison [5] illustrates the need for CT, dimensional and mechanical endpoints in addition to visible surface inspection.

15. Protect slender and weak green features

Recoating imposes hydrodynamic forces on existing features. The Zhang study combined simulation and experiment for slender rods in high-viscosity ceramic stereolithography [6]. Its material regime lies outside this review, but the mechanism warns that geometry and green stiffness belong in the challenge set.

For low-viscosity resins, verify that repeated flow does not bend, detach or fatigue delicate features. Keep this structural check distinct from layer-uniformity measurement.

16. Design an identifiable artefact matrix

Include blank regions, broad flats, deep and shallow cavities, isolated islands, dense cross-sections, narrow flow paths, abrupt transitions and bubble traps. Vary sweep direction, platform speed, layer thickness and wait time. Replicate across build position and independent days.

Measure pre-exposure liquid height or interface, green layer thickness, final geometry and void population. Use matched static-cure controls to isolate fluid effects.

17. Define exposure readiness as a non-compensatory gate

The next exposure may begin only when all required variables meet limits: gap filled, height or interface within tolerance, ripple below limit, no unacceptable bubble in the exposure region, and composition within the declared stability window. A fast average refill does not compensate for one dry corner or persistent bubble.

Record the actual delay and state, not only the programmed delay.

18. Monitor drift through the build

Track resin temperature, viscosity proxy, global level, cycle force or pressure, refill time, surface signal and bubble events where risk justifies it. Early and late layers should be compared because warming, evaporation, material consumption and contamination can change dynamics.

ER-245 owns thermal control and ER-246 owns global level control. ER-244 uses their outputs to determine whether the layer is ready.

19. Transfer and requalification

Revalidate after changes to resin lot, colour, filler or pigment, vat, membrane, blade, pump, platform trajectory, layer thickness, temperature range, part cross-section or software timing. A shorter wait time is a new process claim.

Transfer should preserve relevant *Re*, *Ca*, *Bo*, geometry ratios and wetting state where similarity is asserted, followed by printed validation.

20. Non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Fluid state	Rheology, temperature and shear history	Using one catalogue viscosity
Refill	Geometry-resolved gap filling	Inferring refill from platform motion
Interface	Measured height or ripple tolerance	Calling a fixed pause settling proof
Gas	Bubble source, size, location and fate	Treating every void as optical undercure
Composition	Stability over build and idle time	Assuming low viscosity means homogeneous
Validation	Independent cycle and geometry challenges	Optimising on one flat coupon

21. Minimum reporting set

Report resin identity, lot, temperature and rheology; particles or pigments; architecture and vat geometry; wetted materials; layer thickness; blade, platform, pump or vacuum motion; speed, distance and pressure histories; refill path; contact behaviour; pre-exposure interface criterion; actual wait time; free-surface or gap measurements; bubble detection and exclusions; compositional stability; artefact geometry and cross-section; repeated-layer drift; green and final measurements; uncertainty; acceptance limits; transfer domain; change triggers; and hashes of motion recipes, data and analysis.

22. Knowledge boundary

Primary studies establish that recoating depends on trapped volumes, cavity topography, blade trajectory, viscosity, platform motion and gas-management method [1-6]. Rheology studies show that dispersed composition changes flow response [7]. This evidence supports a state-based qualification framework. It does not establish a universal viscosity limit, blade speed, motion profile, wait time, vacuum level, bubble criterion or sedimentation factor.

23. Limitations

References [1], [3], [4] and [7] were examined at full-text depth; references [2], [5] and [6] at publisher-abstract depth. Several studies concern top-down or highly filled systems and are used only for mechanism identification. This review supplies no proprietary resin recipe, printer timing or commercially actionable recoating setting.

24. Conclusions

Recoating is complete only when the exposure region has the intended liquid layer and a qualified fluid state. Refill, interface relaxation, bubble escape and particle sedimentation are different processes and require different observables. A defensible cycle binds rheology, geometry, motion, wetting and gas history to measured exposure readiness, then validates layer thickness and void control across repeated layers. The deliverable is a bounded process window with explicit state tolerances and change control.

References

1. Pham DT, Ji C. A study of recoating in stereolithography. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. 2003;217(1):105-117. <https://doi.org/10.1243/095440603762554659>
2. Kozhevnikov A, Kunnen RPJ, van Baars GE, Clercx HJH. Investigation of the fluid flow during the recoating process in additive manufacturing. *Rapid Prototyping Journal*. 2020;26(4):605-613. <https://doi.org/10.1108/RPJ-06-2019-0152>
3. Kozhevnikov A, Kunnen RPJ, van Baars GE, Clercx HJH. Protocols for minimizing the leading edge bulge in stereolithography. *Progress in Additive Manufacturing*. 2022;7:361-374. <https://doi.org/10.1007/s40964-021-00234-x>
4. Moghadasi H, Mollah MT, Marla D, Saffari H, Spangenberg J. Computational fluid dynamics modeling of top-down digital light processing additive manufacturing. *Polymers*. 2023;15(11):2459. <https://doi.org/10.3390/polym15112459>
5. Lee JE, Lee JH, Lee SW, Yoon HS, Park J, Ha CW. Impact of recoater method in stereolithography: a comparative analysis of print quality and material properties. *International Journal of Precision Engineering and Manufacturing*. 2025;26:1235-1246. <https://doi.org/10.1007/s12541-024-01172-8>
6. Zhang K, Liu B, Li T, Luo G, Li S, Duan W, Wang G. Simulation and experimental analysis on the deformation rate on slender rod parts during the recoating process in high viscosity ceramic stereolithography. *International Journal of Advanced Manufacturing Technology*. 2023;124:349-361. <https://doi.org/10.1007/s00170-022-10540-5>
7. Reynolds J, Unterhalter J, Francoeur M, Bortner M, Raeymaekers B. Viscosity of mono- and polydisperse mixtures of photopolymer and rigid spheres for manufacturing of engineered composite materials using vat photopolymerization. *Advanced Engineering Materials*. 2024;26:2301630. <https://doi.org/10.1002/adem.202301630>

Copyright

© 2026 Juan Segurolo. All Rights Reserved.