

Grayscale and Spatial Dose Modulation in Vat Photopolymerisation: Local Conversion, Surface Shape and Property Gradients

A calibration and validation framework for intentional spatial response

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Abstract

Grayscale vat photopolymerisation uses spatially varied exposure to produce an intended field of conversion, surface height or material response. The digital image is only the first link in a chain. Grayscale code, irradiance, exposure dose, local reaction history, conversion, network state and mechanical property are not interchangeable. Projector nonlinearity, oxygen inhibition, absorption, scattering, diffusion, heat, accumulated layer exposure, shrinkage and post-treatment can make the response nonlocal, nonlinear and history dependent. Equal nominal dose delivered through different intensity-time pairs may not be equivalent, and a conversion gradient does not uniquely establish a modulus, toughness or residual-monomer gradient.

This review establishes a qualification framework for intentional spatial dose modulation in vat photopolymerisation. It requires code-to-irradiance calibration, reciprocity testing, spatially resolved conversion and property measurements, separation of intended gradients from unintended geometry bias, and prospective validation on withheld spatial patterns. Direct grayscale-DLP studies demonstrate functionally graded materials, reaction-diffusion behaviour, polymer blends, organogel-to-thermoset transitions, shape-memory structures, stress-oriented property design and machine-learning-assisted optimisation. These examples establish feasibility but remain bound to their chemistries, post-treatments, apparatus and load cases. Dose-zoning studies further show that cross-layer accumulation can govern surface and internal features. No universal grayscale-to-dose curve, conversion-to-property map, minimum gradient length, modulus range, surface-height response or reciprocity rule follows. Qualification must preserve the complete material, optical, thermal and spatial state.

Keywords: grayscale DLP; spatial dose; local conversion; property gradient; surface relief; reaction diffusion; exposure reciprocity; qualification

1. Significance and scope

Spatial dose modulation can create compliant hinges beside rigid frames, graded lattices, controlled surface relief or locally adjusted cure. It can also create unintended residual monomer, shrinkage, distortion and weak transition zones. A successful image is therefore not enough; the intended response field must be measured.

ER-242 addresses intentional spatial modulation within and across layers. ER-241 instead compensates unwanted geometry error.

1.1 Corpus boundary

ER-002 retains cross-platform process equivalence. ER-010 retains dimensional metrology. ER-027 retains conversion metrology. ER-035 retains critical exposure and penetration depth. ER-044 and ER-076 retain formulation-driven attenuation and scattering. ER-059 retains sequential dual-cure networks. ER-071 retains in-situ sensing and closed-loop control. ER-171 retains design values and allowables. ER-174 retains optical-state measurement and drift. ER-181 retains post-cure dose delivery. ER-182 retains network-state metrology. ER-197 retains wavelength-selective photochemical addressing. ER-203 retains radiometric traceability. ER-205 retains cure-state mapping. ER-241 retains geometry compensation. ER-243 retains pixel geometry and anti-aliasing. ER-242 owns intentional spatial dose modulation and the qualification of intended conversion, surface-shape and property fields within a declared material and optical state.

2. Preserve the control chain

For a pixel or spatial coordinate x , write

$$g(x) \rightarrow I(x,t) \rightarrow H(x) \rightarrow \alpha(x) \rightarrow S(x) \rightarrow P(x),$$

where g is grayscale code, I is irradiance, $H = \int I dt$ is nominal dose, α is conversion, S is network state and P is a property. Each arrow requires calibration or a justified model. None is universally one-to-one.

3. Calibrate grayscale code to irradiance

Measure irradiance at multiple codes, field positions, times and thermal states. Record bit depth, firmware, image processing, colour channel, gamma or lookup-table behaviour. Quantisation and clipping can remove intended smoothness.

A linear 8-bit image does not establish linear optical power. The calibration should be repeated after source, projector, optical-window or focus changes.

4. Test intensity-time reciprocity

Equal nominal dose can be delivered with low intensity for a long time or high intensity briefly. Photoinitiator depletion, oxygen inhibition, radical termination, diffusion and heating can make these histories different.

At representative grayscale levels, compare conversion, gel state, surface shape and target property for several intensity-time pairs. A reciprocity relation is valid only inside the tested domain.

5. Account for nonlocal reaction and diffusion

Montgomery and co-workers developed and experimentally compared a reaction-diffusion model for grayscale DLP [2]. The study shows that species diffusion can broaden cured features beyond purely optical exposure. Its model agreement on simple structures does not validate all coupled mechanisms or arbitrary geometries.

Measure transition width at relevant spatial frequencies and orientations. A single step edge does not establish response to an island, checkerboard or multilayer gradient.

6. Accumulated dose couples layers

Energy intended for one layer can penetrate into earlier material, while later exposures can further cure a region. Surface, bottom, roof and internal-void responses therefore differ. Luo and co-workers used dose and zoning control to manage accumulated exposure in microfluidic structures [8]. Their sequence supports layer-aware control, not a universal microchannel recipe.

7. Define the intended field before printing

The target may be conversion $\alpha(x)$, height $h_t(x)$, modulus $E_t(x)$, strain capacity or another response. These targets are not equivalent. Define spatial resolution, acceptable transition width, extrema and uncertainty before inverse mapping.

When geometry and property are both critical, specify two independent loss functions and non-compensatory limits.

8. Conversion requires spatially resolved measurement

Select a method with adequate sampling volume and depth sensitivity. Report whether conversion is measured at the surface, through thickness or after sectioning. Washing and post-cure can alter the state between printing and measurement.

Spatial averaging can make a sharp but displaced transition resemble a smooth correct gradient. Register measurement coordinates to the commanded pattern.

9. Conversion does not uniquely determine properties

Modulus, strength, toughness, damping and residual extractables depend on network chemistry, vitrification, post-cure, physical age and defects as well as conversion. Establish each response with local or micro-specimen tests and appropriate uncertainty.

Kuang and co-workers achieved broad functional gradients using grayscale exposure plus a two-stage hybrid cure [1]. The secondary thermal chemistry is essential, so the reported property range is not a generic grayscale response.

10. Specialized chemistries demonstrate possibility, not transfer

Yue and co-workers used grayscale-controlled degree of cure to span organogel-like and thermoset states [4], then used related heterogeneous states in cold-programmed shape-morphing structures [5]. Hergert and co-workers coupled grayscale printing to monomer infusion and secondary polymerisation [3].

These are direct demonstrations of spatial control. Their property ranges, residual sensitivity, swelling response and programming laws cannot be transferred to conventional permanent networks.

11. Post-treatment can amplify or erase a gradient

Washing can extract under-reacted species preferentially. Thermal or optical post-cure can homogenise conversion or alter contrast. Secondary swelling can intentionally transform composition, as in [3]. Record the complete post-treatment field, including shadowing and temperature.

Measure both before and after post-treatment when the mechanism depends on an intermediate state.

12. Differential shrinkage creates geometry coupling

Regions with different conversion or network formation may shrink differently, producing curvature, warpage or interfacial stress. The printed surface may therefore reflect both intended relief and mechanical deformation.

ER-241 owns correction of unwanted geometry. ER-242 must report the geometry consequence of its property design rather than silently correcting it inside a property metric.

13. Surface shape needs independent metrology

For target relief $h_t(x)$, report measured height $h_m(x)$, registration, lateral resolution and missing regions. A useful error field is

$$eh(x) = h_m(x) - h_t(x).$$

Do not use a single roughness statistic to represent low-frequency shape, edge placement and high-frequency texture. Internal surfaces require a validated measurement method.

14. Property-gradient optimisation is model dependent

Valizadeh and co-workers optimised grayscale property distributions to reduce stress concentration and validated their specific specimens [6]. Nam and co-workers combined dynamic-bond polyurethane-acrylate resins with machine-learning-based gradient design [7]. These studies support target-field optimisation and experimental validation.

The solution remains conditional on constitutive model, load case, resin family and training space. A predicted low stress is not a material qualification by itself.

15. Avoid training-validation leakage

Separate coupons used to fit code-to-property maps from patterns used to select models and from prospective spatial holdouts. Hold out new gradient wavelengths, directions, shapes and load cases.

If the inverse model is retrained after viewing holdout results, reserve a new untouched set. Cross-validation within one coupon family does not establish transfer to a component.

16. Quantify spatial resolution and transition zones

Report commanded and measured transition widths, overshoot, ringing, anisotropy and field-position dependence. A minimum printable gradient length is not universal; it depends on optics, chemistry, diffusion, layer history and metrology.

For discrete regions, inspect the interface for residual monomer, cracks or weak zones. For continuous fields, verify monotonicity and local variance.

17. Separate functional performance from local calibration

A graded component can pass a global load test while its local field differs from design. Conversely, local property coupons can match while component stress redistribution differs. Require both field validation and functional validation.

Shape-memory demonstrations [5] and stress-oriented optimisation [6,7] are application evidence for their designs, not universal approval of grayscale gradients.

18. Non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Radiometry	Code-to-irradiance map by field position	Grayscale code as dose
Kinetics	Reciprocity and reaction-diffusion checks	Equal nominal dose as equal cure
Conversion	Registered spatial measurement	Dose as conversion
Network	Post-treatment and residual-state evidence	Conversion as complete material state
Property	Local calibration with uncertainty	Conversion as modulus or toughness
Geometry	Surface and internal feature metrology	Intended gradient hiding distortion
Validation	Prospective spatial and component holdout	Training fit as qualification

19. Transfer domain

Define the qualified state as

$$Q = \{\text{printer, wavelength, field, resin, batch, temperature, layer, exposure history, wash, postcure, age}\}.$$

Transfer outside this set requires bridging evidence. Similar nominal grayscale or initial modulus does not prove an equivalent spatial response.

20. Minimum reporting set

Report resin, batch and formulation class; printer, wavelength and field position; layer thickness; grayscale bit depth and image pipeline; code-to-irradiance calibration; exposure time and sequence; temperature; reciprocity test; conversion method and spatial resolution; post-treatment; target and measured fields; local property tests; geometry and transition metrics; calibration, model-selection and holdout split; uncertainty; invalidations; and acceptance decision.

Archive source images, irradiance maps, exposure schedules, registered field data, model versions and component results.

20.1 Treat residual material as a local endpoint

Low-dose regions can retain more extractable or unreacted material than high-dose regions. A component-average gel fraction or extractables result can conceal the most weakly cured zone. Where safety, dimensional stability or ageing depends on residual material, sample the low-dose state directly or use a spatial method with sufficient sensitivity.

Washing can change both composition and dimensions preferentially in those regions. Record mass change, solvent history and drying before comparing mechanical gradients. A property contrast produced partly by removable material is not equivalent to a stable crosslink-density gradient.

20.2 Test gradient durability

Initial spatial contrast may evolve during post-cure, storage, thermal exposure, humidity or service loading. Repeat registered conversion, shape or local-property measurements after relevant conditioning. The durability endpoint belongs to the intended function: hinge angle, stress redistribution, surface relief or another declared response.

A gradient that is accurate at manufacture but homogenises or cracks during use has not passed long-term qualification. Conversely, some evolution may be acceptable if its magnitude and direction were prospectively bounded. Ageing and environmental tests must retain the same spatial registration used for the initial field.

Include uniform high-, middle- and low-dose controls from the same build. These controls separate gradient-interface effects from the behaviour of each local state. Without them, a failure near a transition cannot be assigned confidently to spatial coupling, the weaker constituent state or global processing variability.

21. Knowledge boundary

The literature demonstrates substantial control using specialized two-stage, blend, organogel, shape-memory and dynamic-bond systems [1,3-7], together with reaction-diffusion and dose-zoning methods [2,8]. Those results do not establish universal response functions.

This review provides no universal grayscale-to-dose curve, conversion-to-property map, minimum gradient length, modulus range, surface-height response or exposure-reciprocity rule.

22. Limitations

References [1] through [8] were examined at publisher-abstract depth. The evidence supports the bounded mechanisms and qualification architecture stated here, but does not establish transferable property ranges, gradients or exposure-response functions.

23. Conclusions

Grayscale control is a chain from digital code to delivered irradiance, dose, conversion, network state and property. Every link can be nonlinear, nonlocal and history dependent. Qualification requires spatial metrology, post-treatment control and prospective holdouts. Specialized chemistries prove feasibility without supplying generic values. Intended property fields and unintended geometry errors must remain separate objectives, linking ER-242 to but not merging it with ER-241.

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