

Optical Attenuation and Cure-Profile Physics in Particle-Filled Vat Photopolymerisation: Absorption, Scattering, Refractive-Index Contrast and Feature Broadening

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Statement of Significance

A particle-filled photopolymer cannot be qualified by cure depth alone. Particles can absorb, scatter, redirect or transmit the incident light, and lateral overgrowth may evolve independently of penetration depth. This review defines a source-traceable cure-profile architecture that separates forward attenuation, side-scattered cure, refractive-index contrast, filler state and chemical threshold. It requires depth, width and conversion measurements to be reported together before a filled resin is described as high resolution, deeply curable or transferable between machines.

Keywords: vat photopolymerisation; particle-filled resin; optical attenuation; light scattering; absorption; refractive-index contrast; cure depth; cure width; feature broadening; ceramic suspension; composite resin; qualification.

Abstract

Particle-filled resins support ceramic, conductive, dental, optical and structural functions, but the same dispersed phase that creates functionality also changes how light propagates and how the cure boundary develops. This review separates absorption, forward transmission, multiple scattering and side-scattered polymerisation, then links them to powder volume fraction, particle size distribution, morphology, agglomeration, refractive-index mismatch, matrix composition, photoinitiator and absorber content. It adopts the source-defined depth sensitivity, depth critical energy, width sensitivity, width critical energy, excess width and broadening depth as reporting variables rather than universal material constants. The literature shows that the effect of fillers is not monotonic: opaque or highly mismatched particles can reduce penetration, low refractive-index contrast can suppress broadening, and translucent glass microspheres can increase cure depth at low exposure because transmission competes with scattering. Resin composition, filler dispersion and particle-size distribution can shift cure depth and lateral growth in opposite directions. A minimum qualification matrix is proposed that records the optical spectrum, incident pattern, depth and width profiles, conversion, gel criterion, filler state, rheology, ageing and printed geometry. The review does not prescribe a universal filler loading, attenuation coefficient or cure target and does not infer final ceramic, electrical, dental or biological performance from optical printability.

1. Scope and evidence-selection method

ER-76 addresses the optical and photochemical mechanisms by which dispersed particles change the spatial cure profile of SLA, DLP, LCD/MSLA and closely related vat-photopolymerisation systems. The focus is the liquid formulation and the green cured profile: depth, lateral width, broadening, conversion and their dependence on particle and matrix state. Final debinding, sintering, electrical function, antimicrobial performance and device qualification are outside scope except where a source-specific result demonstrates why optical printability cannot stand in for final performance.

The evidence base prioritises experiments that vary a filler, absorber, refractive-index contrast, particle-size distribution, resin composition or dispersion state while measuring cure depth, cure width, conversion or printed geometry [1-10]. Classical ceramic-suspension studies are used because they define the depth-width vocabulary and isolate absorption and scattering. More recent translucent, conductive and dental composites test whether those mechanisms transfer to non-ceramic functions. No numerical value is pooled across formulations, wavelengths or instruments.

2. A filled-resin cure profile is not one-dimensional

A conventional working curve compresses a three-dimensional optical field into cured depth versus incident exposure. This is useful only when the lateral profile remains controlled and when the selected gel or solidification criterion is unchanged. Filled formulations can violate both assumptions. A resin may cure to the desired depth while the line balloons laterally below the surface, or it may show a lower critical energy because particles immobilise monomer while simultaneously losing optical penetration [2-4,7].

The minimum cure-profile record therefore contains the incident illumination geometry, the full cross-section of the cured feature and the state criterion used to identify the boundary. Depth and width must be fitted independently. Degree of conversion, green integrity and final post-cure properties are additional states and must not be inferred from the geometry alone [6,7,10].

Table 1. Optical phenomena and the measurements needed to distinguish them.

Phenomenon	Direct or primary measurement	Possible cure-profile consequence	Interpretation boundary
Absorption by initiator, dye, matrix or filler	Spectral absorbance/extinction at the printing wavelength; composition and path length.	Reduced forward intensity; altered depth sensitivity and critical exposure.	Absorbance does not identify scattering direction or conversion.
Forward transmission through translucent particles	Collimated and total transmission; particle and matrix refractive index.	Deeper cure can persist or increase despite added filler.	A clear appearance does not prove low broadening.
Elastic scattering and multiple scattering	Angular scattering or integrating-sphere measurement; particle size and morphology.	Lateral broadening, blurred edges and redistributed dose.	Haze or total transmittance alone may miss the printing geometry.
Side-scattered cure	Cross-sectional cure width versus depth and exposure.	Excess width can grow faster than cure depth.	A depth-only working curve cannot detect this failure.
Chemical threshold and inhibition	Conversion or gel response versus intensity and time.	Shift of critical depth and width exposures.	Optical attenuation and chemical threshold are coupled but not identical.
Dispersion state and sedimentation	Particle-size distribution, microscopy, stability and time-resolved rheology.	Spatially drifting optical field and non-reproducible profile.	Nominal filler fraction does not establish local optical state.

3. Depth sensitivity, width sensitivity and broadening depth

Tomeckova and Halloran measured cure depth in silica and alumina suspensions and showed that the reciprocal depth-sensitivity parameter changed systematically with photoinitiator and dye concentration under their absorption model [1]. Gentry and Halloran then demonstrated that the cured cross-section requires a second semilogarithmic relation for the excess lateral width [2]. In the source notation, cure depth C_d is described by depth sensitivity S_d and depth critical energy E_d :

$$C_d = S_d \ln(E/E_d)$$

The excess width w_{ex} is one-half of the difference between the measured cured width and the illumination width, and its exposure dependence is described separately by a width sensitivity S_w and width critical energy E_w [2]. The broadening depth D_b is the cure depth at which measurable broadening begins. These variables are source-defined descriptors, not universal constants: the illumination profile, boundary criterion, wavelength, temperature and formulation must accompany every fitted value.

A formulation can therefore have an apparently favourable depth sensitivity and still be unsuitable for narrow features if D_b lies below the intended cure depth. Conversely, a low width sensitivity does not establish adequate depth, conversion or interlayer integrity. The complete profile is the engineering object.

4. Absorption controls depth and width through different thresholds

Increasing photoinitiator or inert absorber concentration changed both depth and width sensitivities in the ceramic suspensions studied by Gentry and Halloran [3]. Their absorption model described the sensitivity terms, while an inhibitor-exhaustion model described the depth and width critical exposures. This separation matters: an additive can change the rate at which light decays and also change the chemical exposure required to create a stable boundary.

Absorbers are therefore not generic resolution agents. A higher absorber loading can reduce penetration and lateral spread, but it can also raise the exposure needed at depth, increase through-thickness conversion gradients or narrow the process window. The selected dosage must be evaluated in the complete particle-containing formulation rather than transferred from the unfilled matrix.

5. Scattering and refractive-index contrast govern feature broadening

The normalized refractive-index contrast used by Gentry and Halloran was defined as the absolute particle-matrix index difference divided by the matrix index [2,4]:

$$\Delta n/n_0 = |n_0 - n_p| / n_0$$

Here n_0 is the refractive index of the liquid monomer solution and n_p is the particle refractive index, both at the relevant wavelength and temperature. The cited studies found that broadening depth decreased with the logarithm of refractive-index contrast for the examined ceramic systems [2,4]. The relationship was empirical and depended on the initiator concentration, illumination and suspension; it must not be treated as a universal master curve.

Low refractive-index contrast is consequently a route to deep, narrow curing only when the particle distribution, absorption and chemical threshold remain controlled. Huang and co-workers used a reactive monomer to reduce the contrast in a β -tricalcium-phosphate suspension and reported 52 vol% solids, 5.76 Pa·s at 100 s⁻¹ and cure depth above 200 μ m without observed broadening in that formulation [5]. Those values are implementation-specific, not general acceptance limits.

6. Particle loading is not a monotonic optical variable

Filler fraction can change the number of scattering events, the optical path length, particle-particle spacing and the fraction of light transmitted through the dispersed phase. In the ceramic systems examined by Gentry and Halloran, powder volume fraction did not control broadening depth in the same way as refractive-index contrast [4]. That source-specific finding does not mean solids loading is optically irrelevant: loading can still change attenuation, viscosity, sedimentation, conversion and the probability of aggregation.

Translucent particles illustrate why a one-direction rule fails. Liang and co-workers found that, for glass microspheres in a diacrylate/epoxy resin, cure depth depended on competing scattering and transmission and increased with filler fraction at low exposure dose [6]. The result contrasts with the usual expectation for opaque fillers. Filler identity, size distribution and transmission must therefore be measured rather than inferred from mass fraction.

7. Particle size, morphology and dispersion state

Particle size changes both optical interaction and rheology. Coarser silicon-nitride particles showed lower absorbance and higher cure depth in the study by Huang and co-workers, but the coarse-particle material had poorer mechanical performance; a bimodal coarse:fine ratio of 3:7 was selected as a compromise for the reported system [8]. Fine particles increased specific surface area, viscosity and absorbance while improving densification and final strength. Optical optimisation and final-material optimisation therefore need not select the same distribution.

Agglomeration changes the effective scattering-unit size and can create local shadows or high-transmission channels. Sevriugina and co-workers showed that carbon-filler dispersion and matrix affinity changed critical energy, penetration depth, viscosity and functional percolation [7]. Improved dispersion reduced the critical curing energy in the tested systems but deteriorated optical clarity and penetration depth. A filler that is beneficial electrically can therefore consume optical process margin.

8. Matrix composition and filler optics are coupled

The liquid matrix sets refractive index, absorption, viscosity, initiator solubility and radical mobility. Changing monomer, oligomer, diluent or plasticizer can therefore shift depth and lateral growth even when the ceramic fraction and incident dose remain constant. McAleer and co-workers reported cure depths of 222 μ m for the monomer baseline, 308 μ m after adding polyethylene glycol, and 155 and 178 μ m for two oligomer-containing formulations at 15 mJ/cm²; the polyethylene-glycol formulation also showed the greatest lateral growth [9].

Those results demonstrate that a depth increase is not automatically a resolution improvement. The same matrix change can improve penetration while worsening projected-image fidelity or surface form. Refractive index, viscosity and reaction kinetics should be measured together before assigning mechanism.

Table 2. Source-specific findings illustrating non-transferable cure-profile trade-offs.

System and source	Observed optical/cure behaviour	Boundary on use
Ceramic suspensions with initiator and dye variation [1,3]	Depth and width sensitivities and their critical exposures changed with absorber concentration.	Do not transfer fitted parameters to another absorber, wavelength or particle state.
Silica, mullite, alumina and zircon suspensions [2,4]	Depth and lateral broadening followed different semilog relations; D_b decreased as normalized RI contrast increased.	The empirical contrast relation belongs to the tested illumination and chemistry.
52 vol% β -TCP with low-contrast reactive matrix [5]	5.76 Pa·s at 100 s ⁻¹ and cure depth >200 μ m without observed broadening.	One optimized suspension does not define a universal viscosity, loading or depth target.
Translucent glass microspheres [6]	At low exposure, cure depth increased with filler fraction because transmission competed with scattering.	Opaque-filler intuition cannot be applied to translucent fillers.

System and source	Observed optical/cure behaviour	Boundary on use
Carbon black, nanotubes and graphene [7]	Dispersion reduced critical energy but increased viscosity and reduced optical clarity and penetration depth.	Functional percolation and optical printability are separate optimisation axes.
Bimodal Si ₃ N ₄ particles [8]	Coarse particles increased cure depth through lower absorbance; fine particles supported better final mechanics.	Cure depth alone cannot select the final particle distribution.
Al ₂ O ₃ with matrix-composition changes [9]	PEG increased depth and lateral growth; oligomer reduced both at constant dose.	Matrix modification can move depth and width in the same or different directions.
ZnO/SiO ₂ dental composite, 0-10 vol% [10]	Cure depth trended downward with filler, without a significant between-group difference; conversion remained about 46-49%.	State the statistics and do not upgrade a trend to a validated monotonic law.

9. Cure geometry, conversion and material state must remain separate

A cured profile identifies a boundary produced by the chosen test. It does not establish uniform conversion, crosslink density or green strength. Liang and co-workers measured degree of cure together with curing depth and geometry, showing that a filler can alter these responses in different directions [6]. Sevriugina and co-workers likewise reported that dispersed carbon fillers reduced critical energy while decreasing penetration depth [7].

The ZnO/SiO₂ dental study provides an additional caution: filler addition produced a downward cure-depth trend, but the differences were not statistically significant, and the reported conversion values remained in a narrow range of approximately 46-49% under the selected photo-DSC conditions [10]. The authors attributed the trend to scattering and attenuation from refractive-index mismatch. ER-76 retains the statistical qualifier and does not treat the result as a universal concentration law.

10. Measurement architecture for a filled-resin cure profile

The optical test must reproduce the printing wavelength, spectral bandwidth, incident angular distribution and exposure range. The illumination width or projected pixel mask must be recorded so that excess width can be separated from the source geometry. Cross-sectional measurement should capture the complete cured profile, including sub-surface ballooning, not only the top-surface edge.

A single fit is insufficient. The minimum dataset includes raw depth and width against exposure, the stated boundary criterion, spectral transmission or absorption, filler identity and state, and a conversion or gel-related measurement. Replicate profiles should be taken at more than one vat location and after relevant residence or storage intervals. A profile that changes with time is a formulation-state problem, not only a printer-calibration problem.

Table 3. Minimum qualification matrix for a particle-filled VPP cure-profile claim.

Domain	Minimum record	Decision supported
Optical source	Wavelength distribution, irradiance map, pattern or beam width, exposure time and dose.	Defines the incident field.
Liquid matrix	Monomer/oligomer class, initiator, absorber, diluent, refractive index and temperature.	Defines absorption and chemical threshold.
Particles	Material, loading basis, size distribution, morphology, refractive index and absorption state.	Defines the dispersed optical phase.
Dispersion state	Mixing route, agglomeration, microscopy, sedimentation or stability interval and sampling position.	Shows whether the nominal composition is spatially realised.
Depth profile	Raw C _d versus exposure, criterion, fit range, S _d /E _d or equivalent and uncertainty.	Bounds penetration.
Width profile	Incident width, total cured width, excess width, S _w /E _w or equivalent, D _b and uncertainty.	Bounds lateral broadening.
Chemical state	Conversion or gel criterion through relevant depth/width positions; green recovery where needed.	Separates geometry from network state.
Printed geometry	Thin walls, gaps, holes, internal channels, build position, orientation and dimensional map.	Tests translation from coupons to features.
History and reuse	Batch, age, storage, vat residence, mixing and reuse cycles.	Tests stability of the optical state.

Domain	Minimum record	Decision supported
Final function	Application-specific mechanical, thermal, electrical, ceramic, dental or biological tests.	Prevents optical printability becoming a final-performance claim.

11. Standards and method boundaries

ISO/ASTM 52940:2025 specifies ceramic-slurry characterization including composition, solids content, dynamic viscosity, particle-size distribution, chemical composition and dispersion stability [S1]. It strengthens the feedstock record but does not define a cure-width, broadening-depth, refractive-index-contrast or through-profile optical qualification method. ISO 13468-1:2019 and ISO 14782:2021 address total luminous transmittance and haze for transparent, substantially colourless planar plastics within their stated scopes [S2,S3]. Filled, absorbing or highly scattering liquid resins and process-specific angular fields can fall outside those scopes.

No published ISO, ASTM or DIN method is identified here as a complete qualification standard for the coupled depth-width cure profile of a particle-filled VPP resin. ISO/ASTM 52900:2021 supplies vocabulary [S4]. A laboratory method must therefore declare instrument geometry, spectrum, path length, boundary criterion, particle state and uncertainty rather than citing a general optical or AM standard as automatic validation.

12. Failure modes and interpretation errors

Table 4. Common interpretation failures in filled-resin cure studies.

Observation	Interpretation error	Required response
Target cure depth reached	High resolution claimed.	Measure cured width, D _b and critical features.
Depth decreases with filler	Scattering declared as the only mechanism.	Measure absorption, transmission, RI contrast and dispersion.
Depth increases with filler	Filler called optically transparent.	Separate forward transmission from side scattering and conversion.
Low haze measured	Low process broadening inferred.	Use printing-wavelength angular and cured-profile measurements.
Same nominal filler fraction	Equivalent optical state assumed.	Record particle distribution, agglomeration, history and sampling position.
Lower critical energy	Better printability claimed.	Check penetration, width, rheology and green integrity.
Low RI contrast calculated	Deep narrow cure guaranteed.	Verify actual particle/matrix indices at wavelength and temperature plus absorption.
Fine particles improve final strength	Fine distribution selected without cure testing.	Measure absorbance, viscosity, depth and width for the selected distribution.
Good coupon geometry	Complex internal features assumed valid.	Test thin walls, gaps, holes and build-volume positions.
Ceramic or functional filler identified	Final function inferred.	Perform final-state, application-specific qualification.

13. Scope boundaries within the Engineering Review series

- ER-27 addresses conversion metrology and spatial cure heterogeneity. ER-76 uses conversion as a state check but is restricted to particle-controlled optical attenuation and the depth-width cure profile.
- ER-35 and ER-36 address dispersion stability, sedimentation, rheology and recoating. ER-76 records those states only because they change the optical field; it does not replace colloidal or recoating qualification.
- ER-23 addresses implantable-ceramic feedstock-to-final-state qualification. ER-76 stops at the green optical cure profile and does not infer phase, density, bioactivity or implant suitability.
- ER-70 addresses fracture toughness and damage tolerance, and ER-73 addresses interlayer cohesion and mechanical anisotropy. Neither mechanical endpoint follows from cure depth or broadening alone.
- ER-75 addresses the whole-volume operating window of tomographic VAM. ER-76 concerns local depth-width curing in layer-wise VPP and does not treat integrated tomographic dose reconstruction.
- Generic optical-part performance, refractive-index selection and optical ageing remain outside scope. ER-76 uses refractive index only as an input to particle-matrix scattering.

14. 3Dresyns implementation boundary

Current 3Dresyns pages include Light Blocker or resolution additives positioned to reduce penetration, scattering or overcure, photoaccelerants positioned to increase cure speed, and reactive composite concentrates containing ceramic or reinforced particles [M1-M4]. Those pages establish product identity and intended formulation role only. They are not independent evidence of a transferable S_d , E_d , S_w , E_w , D_b , attenuation coefficient or refractive-index-contrast window.

A formulation additive can improve one axis and worsen another. Increasing reactivity may increase depth or lateral growth. Increasing attenuation may reduce overcure while raising the exposure needed at depth. Adding an opaque or high-index filler may change absorption, scattering, viscosity and sedimentation at the same time. Every change therefore requires the complete formulation to be recalibrated in the selected printer and geometry.

No current standard 3Dresyns product is identified in this review as independently validated across machines by a published coupled depth-width cure-profile programme. A future claim would require controlled formulation identity, particle state, optical and rheological characterization, profile maps, conversion or gel evidence, history stability, uncertainty and application-specific final testing.

15. Design rules

- Measure cured width as well as depth.
- Record the incident pattern or beam width used to define excess cure.
- Treat S_d/E_d and S_w/E_w as separate fitted pairs.
- Report the boundary criterion and uncertainty for every profile.
- Measure particle and matrix refractive indices at the printing wavelength and relevant temperature.
- Separate absorption, transmission and scattering rather than using opacity as a mechanism.
- Document particle-size distribution, morphology, agglomeration and dispersion history.
- Rebuild the optical map after changing filler, matrix, initiator, absorber or dispersant.
- Pair cure geometry with conversion or gel-state evidence.
- Test complex features and more than one vat position.
- Do not infer final function from optical printability.
- Requalify after storage, reuse or remixing that can change the particle state.

16. Research priorities

Priority work should connect angular or spatially resolved optical transport to the actual cured cross-section under projection geometries used by modern DLP and LCD systems. Interlaboratory comparison is needed for width sensitivity, broadening depth and the boundary criterion, with shared particle standards and explicit uncertainty. Dynamic measurements should track changes in dispersion, refractive index and absorption during vat residence and repeated exposure.

Further work is required on non-opaque functional fillers, where transmission and scattering compete, and on machine-learning or physics-informed models that predict the full cure shape without hiding the underlying measurements. Models should be validated on thin walls, gaps and internal features rather than on depth coupons alone.

17. Conclusions

Particle-filled vat photopolymerisation is governed by a coupled depth-width cure problem. Absorption controls forward attenuation, scattering redistributes light, refractive-index contrast influences broadening, and the chemical threshold converts that optical field into a gel or green body. The governing variables are formulation-, wavelength-, particle-, history- and instrument-specific.

A cure-depth working curve is therefore necessary but insufficient. A defensible material record includes the incident pattern, raw depth and width profiles, depth and width fit parameters, broadening depth, refractive-index and absorption data, particle and dispersion state, conversion or gel evidence, rheology, history and feature-level validation.

The central engineering principle is: a filled resin is not high resolution because it cures to the required depth; it is high resolution only when the complete cured profile remains bounded in depth and width while the intended material state and final function are independently demonstrated.

Limitations

This review is a literature-based synthesis and reports no new experimental dataset or quantitative meta-analysis. The cited studies use different particles, matrices, wavelengths, beam or projection geometries, exposure ranges and cure-boundary criteria. Numerical values are retained only with their source conditions and are not proposed as transferable targets.

The depth-width descriptors were developed primarily in ceramic suspensions and require validation before use in another material class. The normalized refractive-index-contrast relation and broadening-depth fits are empirical for the source systems. Transmittance and haze standards are adjacent measurements, not substitutes for a process-specific liquid-resin cure-profile method.

The manufacturer pages were reviewed on 22 August 2026 and may change. No safety, biological, dental, electrical, ceramic-final-state or regulatory claim is made from product positioning or from the optical data reviewed here.

Declarations

Author contributions: Juan Seguro: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests: The author is founder, CEO and CTO of 3Dresyns by Resynr Technologies S.L. Manufacturer documentation is separated from peer-reviewed evidence and is not presented as independent validation.

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

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Standards and series framework

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