

Sequential Dual-Cure Networks in Vat Photopolymerisation: Geometry Fixation, Secondary Network Formation and Property Homogenisation

Juan Segurola, PhD

3Dresyns by Resyner Technologies S.L., Donostia / San Sebastián, Spain

3Dresyns Engineering Review ER-59 · Version 1.2 · 25 August 2026 · No proprietary formulation composition disclosed

Abstract

Vat photopolymerisation normally uses the same photochemical event both to define geometry and to establish a substantial fraction of the final polymer network. This coupling is convenient but restrictive. Optical attenuation, radical termination, oxygen inhibition, vitrification and mobility loss can generate non-uniform conversion through depth and between layers, while increasing exposure to compensate can degrade dimensional fidelity.

Sequential dual-cure systems provide a different materials architecture. A first reaction is used to establish the printable geometry and mechanically stable intermediate state, while a second independently activated reaction subsequently modifies, completes or reorganises the network. Reported implementations include photochemical acrylate fixation followed by thermally activated radical or epoxy reactions, hybrid acrylate-epoxy interpenetrating networks, thermally strengthened interlayer interfaces, and wavelength-orthogonal radical/cationic photopolymerisation capable of producing spatial variations in mechanical properties from a single resin formulation.

The central engineering distinction is that dual cure is not synonymous with conventional post-curing. Additional irradiation or heating that merely advances the same photopolymerisation reaction does not by itself establish a second curing mechanism. A dual-cure material contains deliberately separated reactive pathways whose sequence, latency and interaction influence the intermediate and final network states.

This review develops an engineering framework for analysing such systems in vat additive manufacturing. It considers reaction orthogonality, latent stability, conversion gradients, interpenetrating-network morphology, polymerisation-induced phase separation, interlayer reinforcement, shrinkage and stress accumulation, and the relationship between the printable intermediate state and the final functional state. A stage-resolved qualification framework is proposed in which chemistry, dimensions and mechanical properties are measured after both the printing stage and the secondary cure.

Keywords

vat photopolymerisation; dual cure; sequential curing; stereolithography; acrylate; epoxy; interpenetrating polymer network; dark cure; thermal cure; dual-wavelength photopolymerisation; network morphology

1. Introduction

Vat photopolymerisation creates a solid object by transforming a low-viscosity reactive formulation into a crosslinked network under spatially controlled irradiation.

In the conventional model, optical exposure is expected to perform several tasks simultaneously:

1. establish the boundary of the printed feature; 2. provide sufficient green strength for continued printing; 3. generate adequate interlayer cohesion; 4. produce a sufficiently converted network; 5. approach the mechanical and thermal properties required from the final material.

These requirements are not necessarily compatible.

High conversion during printing can improve green-state strength but can also increase shrinkage, stress and brittleness. Lower exposure can preserve dimensional fidelity but leave a heterogeneous conversion state. Increasing crosslink density can improve stiffness while reducing mobility of residual reactive groups and slowing subsequent conversion.

Dual-curing strategies separate these functions in time or stimulus space.

The first stage can be interpreted primarily as:

geometry fixation + green-state formation

while the second stage performs:

network completion + property development

This separation has been investigated explicitly in additive manufacturing. Fernández-Francos and co-workers reviewed dual-curing systems as materials in which controlled reaction sequencing permits an intermediate printed state followed by activation of a subsequent polymerisation reaction [1]. Uzcategui and co-workers demonstrated a dual-cure acrylate system in stereolithography in which secondary thermal activation increased and homogenised conversion beyond that produced by the printing exposure alone [2].

The resulting design philosophy is fundamentally different from attempting to obtain every final property directly inside the printer.

2. What constitutes a dual-cure system?

The term requires careful definition.

2.1 Conventional post-curing

Consider a conventional acrylate photopolymer containing residual double bonds after printing.

Further irradiation may increase conversion:



Heating may also increase mobility and allow the original photochemical network to continue reacting.

This is an important processing step, but it remains essentially a continuation of the original curing chemistry.

For the purposes of this review:

ordinary continuation of the same cure reaction is not classified as a distinct dual-cure architecture.

2.2 Sequential dual cure

A stronger definition requires two intentionally engineered reaction stages possessing sufficient kinetic or stimulus separation that the material can occupy a useful intermediate state between them.

Conceptually:

Liquid formulation

↓ Cure 1

dimensionally defined intermediate network

↓ Cure 2

final network

The second reaction may:

- polymerise a second functional group;
- activate a second initiator;
- form a second network;
- create covalent connections between structures formed in the first stage;
- trigger network exchange;
- change morphology through reaction-induced phase evolution.

This distinction makes the intermediate state a legitimate engineering state rather than merely an incompletely cured final material.

3. Major dual-cure architectures relevant to VPP

3.1 Photochemical radical cure followed by thermal radical cure

One of the conceptually simplest routes uses photoinitiation during printing and a latent thermal radical initiator during secondary treatment.

Uzcategui et al. incorporated a thermal initiator into an acrylate-based stereolithography resin so that printing generated the initial structure while subsequent heating increased conversion throughout the object [2].

This architecture qualifies as dual cure under the definition in Section 2.2 because a second, independently activated thermal initiating system is deliberately incorporated into the original formulation. The distinction from conventional post-curing lies in the engineered latent initiating system and the separately triggered reaction stage, not necessarily in a change of monomer family.

This architecture can compensate partly for optical limitations because thermal initiation does not require photons to reach the region in which radicals are subsequently generated.

The distinction is:

printing reaction

spatially selective and optically controlled

versus

secondary reaction

non-spatial thermal network completion.

This can be useful for geometries where optical penetration or shadowing produces a conversion gradient.

It also illustrates an important limitation: secondary thermal polymerisation can increase conversion, but it cannot reconstruct geometric information already lost during the first stage.

Therefore:

secondary cure can improve network state

but

secondary cure cannot repair fundamentally incorrect geometry.

3.2 Acrylate fixation followed by epoxy cure

A more strongly differentiated architecture incorporates acrylate and epoxy chemistry in the same formulation.

Konuray and co-workers demonstrated systems in which free-radical acrylate photopolymerisation provides the initial printed network, after which thermal activation causes epoxy polymerisation and further reaction of residual acrylates [3,4].

The sequence can be represented schematically as:

Stage 1

acrylate + photoinitiator + $h\nu$ → crosslinked acrylate-rich intermediate

Stage 2

epoxy + latent thermal chemistry + heat → additional network formation

The final material is therefore not merely a more completely photocured version of the green part.

Its network architecture has changed.

Depending on formulation and cure sequence, the two components may form:

- highly interpenetrated networks;
- nanoscale phase-separated morphologies;
- more clearly separated domains.

Konuray et al. demonstrated that epoxy modification followed by thermal treatment could produce nanoscale phase-separated polyacrylate/epoxy materials and substantially alter the final modulus [5].

Consequently, cure schedule becomes a morphology-processing variable.

4. Network morphology is a processing result

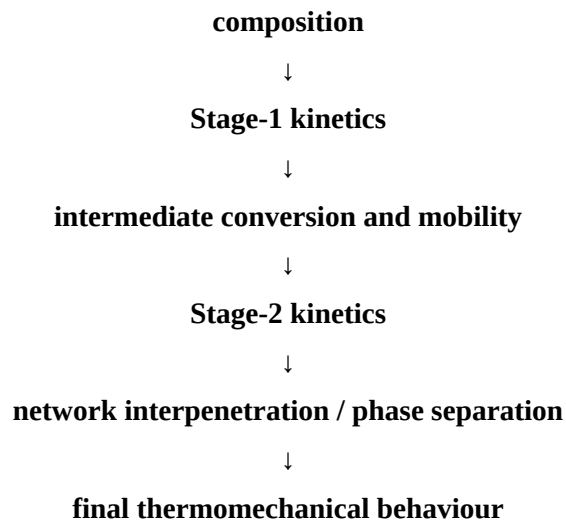
In dual-network materials, final properties cannot be predicted solely from nominal composition.

The same formulation can potentially evolve differently depending on:

- relative rates of the two reactions;
- conversion reached in Stage 1;

- delay before Stage 2;
- secondary-cure temperature;
- vitrification;
- component mobility;
- thermodynamic compatibility;
- reaction-induced phase separation.

This gives a sequence:



This is particularly important because the first cure can progressively immobilise the second reactive component.

A formulation that is homogeneous as a liquid is therefore not necessarily homogeneous after Cure 1 or Cure 2.

Conversely, nanoscale heterogeneity is not automatically detrimental. Controlled phase morphology can contribute to toughness, stiffness or damping behaviour.

The appropriate target is not universal homogeneity.

It is:

a reproducible morphology that delivers the required property state.

5. Interlayer reinforcement

Layerwise VPP introduces another opportunity for sequential chemistry.

Even when each individual layer reaches a useful conversion, interlayer regions can remain mechanically distinct because polymerisation history and available reactive functionality differ across the interface.

Kim, Han and Seo demonstrated a stereolithographic dual-curing strategy in which thermally reactive functionality was incorporated into the printed formulation. Subsequent thermal treatment promoted chemical

reactions across adjacent layers and substantially improved interlayer bonding and mechanical properties without a correspondingly large dimensional penalty in the reported system [6].

This provides an important conceptual distinction.

Conventional post-cure seeks primarily to:

increase conversion

whereas an appropriately designed secondary reaction can additionally:

create new interfacial connections.

For anisotropic printed structures, this distinction can be more important than the average bulk conversion.

A useful qualification programme must therefore test both:

bulk mechanical properties

and

interlayer fracture or orientation-dependent properties.

A tensile-strength increase alone cannot establish that interlayer weakness has been removed.

6. Dual-wavelength curing

Sequential chemistry need not rely on heat.

An alternative is to encode chemical orthogonality spectrally.

Cazin et al. investigated hybrid acrylate-epoxy resins in which 405 nm irradiation predominantly produced free-radical acrylate curing while 365 nm irradiation additionally activated cationic epoxy ring opening [7].

This enabled the formation of different network states from a single resin formulation according to illumination wavelength.

Conceptually:

405 nm

→ predominantly Network A

whereas:

365 nm

→ Network A + Network B

The approach extends dual cure from temporal sequencing toward spatial programming.

Instead of:

print → globally post-cure

the process can become:

select local cure pathway during printing.

This creates the possibility of spatially varying:

- modulus;
- glass-transition behaviour;
- toughness;
- network composition;
- local deformation response.

However, spectral orthogonality is rarely absolute.

Cazin et al. showed that resin composition and photoinitiator concentration influence the independence of the two reactions [7]. Increasing one reactive component can improve a target property while simultaneously increasing unwanted cross-activation.

The relevant parameter is therefore not simply whether two photoinitiators possess different absorption maxima.

The important question is:

How independently can the two network-forming reactions actually be controlled inside the complete resin?

7. Orthogonality

For two reactions A and B, an idealised system would behave as:

Stimulus 1 → A

Stimulus 2 → B

with negligible cross-response.

Real systems more commonly behave as:

Stimulus 1 → A + εB

Stimulus 2 → B + εA

where ε represents unintended cross-activation.

The engineering objective is to make the cross-response sufficiently small for the intended process rather than assuming perfect molecular orthogonality.

For wavelength-controlled systems this requires measurement of:

- initiator absorption spectra;

- source emission spectra;
- molar absorptivity;
- reactive quantum efficiency;
- penetration depth;
- competing absorption from pigments or additives;
- conversion of each functional group under each irradiation condition.

Spectral separation alone is therefore insufficient.

A photoinitiator may absorb weakly at an off-target wavelength yet still initiate enough reaction to destroy the intended material contrast.

8. Latency and storage stability

Sequential curing depends on the second reaction remaining adequately dormant during the first processing

The required condition can be expressed qualitatively as:

$$\text{rate of Cure 2 during printing} \ll \text{rate of Cure 1 during printing}$$

while later:

$$\text{rate of Cure 2 under activation} \gg \text{storage/background rate}$$

This creates a latency window.

If the second chemistry reacts prematurely:

- viscosity can increase during storage;
- vat lifetime can decrease;
- spatial control can be lost;
- green-state properties can drift during a print;
- the intended intermediate state becomes poorly defined.

If the second chemistry is excessively difficult to activate:

- impractical temperatures or times may be required;
- the first network may degrade before the second cure is completed;
- residual reactive species may remain.

Konuray and co-workers reported that the intermediate material remained storage-stable under ambient conditions for at least nine weeks because the epoxy component remained essentially unreacted before thermal activation [3]. This is a study-specific result for the reported formulation and storage conditions, not a universal shelf-life expectation for dual-cure resins.

Storage stability should therefore be regarded as part of dual-cure performance, not simply as a packaging issue.

9. The intermediate state is a designed material state

One of the most useful consequences of dual curing is the possibility of engineering the part between Cure 1 and Cure 2.

Define:

State 0: liquid formulation

State 1: printed intermediate

State 2: fully processed material

A conventional TDS typically reports primarily State 2.

For a dual-cure system that is insufficient.

State 1 determines whether the object can:

- support its own weight;
- retain dimensions;
- be removed from the platform;
- survive washing;
- be assembled;
- be bonded;
- be deformed deliberately;
- undergo a later shape-fixing process.

A vitrimer is a dynamic covalent network whose topology can rearrange through associative bond-exchange reactions while maintaining overall network connectivity. Vitrimeric behaviour therefore requires both suitable exchangeable bonds and an effective exchange pathway; it cannot be inferred from the presence of a catalyst or from a commercial product label alone.

Escríbá-Flores and co-workers reported a dual-cure acrylate/epoxy vitrimeric system whose intermediate state accommodated strains of up to 80%, with an ultimate tensile strength of 0.7 MPa. Following thermal treatment, the reported final state reached an ultimate tensile strength of 66 MPa [8]. The same study demonstrated transesterification-mediated repair and reprocessing. These quantitative results belong to the specific formulation and thermal protocol investigated and are not universal dual-cure performance targets.

Thus:

green-state weakness is not necessarily a formulation defect

provided that:

the intermediate state is sufficiently stable for its intended handling operation.

This opens an additional design dimension for VPP.

10. Dark reaction and delayed network evolution

The term **dark cure** should be used carefully.

Certain initiating mechanisms, particularly cationic polymerisations, can continue after illumination stops because reactive ionic centres can remain active.

This behaviour differs from activation of a separate thermal cure.

Three phenomena should therefore be distinguished:

1. continued photopolymerisation-derived reaction after light removal; 2. thermally activated secondary polymerisation; 3. network exchange or rearrangement after the primary polymerisation is complete.

All three can change properties after the apparent end of printing.

They should not be conflated because their consequences for dimensional stability and process timing differ.

For systems with significant post-exposure reaction, the effective material state becomes time-dependent:

property = f(exposure history, temperature history, elapsed time)

not merely:

property = f(total optical dose).

11. Shrinkage and residual stress

Dual cure solves some problems while introducing others.

Every additional network-forming reaction can generate:

- chemical shrinkage;
- thermal expansion and contraction;
- vitrification stress;
- modulus increase under constraint;
- phase-separation stress.

If Stage 1 geometrically locks the object and Stage 2 subsequently contracts the network, the final dimensions may differ from the printed intermediate.

A useful decomposition is:

$$\epsilon_{\text{total}} = \epsilon_{\text{stage1}} + \epsilon_{\text{stage2}} + \epsilon_{\text{thermal}} + \epsilon_{\text{relaxation}}$$

where the terms denote dimensional strain associated with the corresponding processes.

This expression is an engineering bookkeeping model rather than a universal constitutive equation.

The practical implication is important:

a dual-cure resin cannot be dimensionally qualified using only the geometry measured immediately after printing.

Dimensions should be measured at least:

- after printing;
- after washing/drying;
- after Cure 2;
- after final conditioning.

This requirement separates dual-cure qualification from simple printer calibration.

12. Conversion must be chemistry-specific

A single global “degree of cure” can become misleading when two independently reacting functionalities are present.

For an acrylate-epoxy system, for example, one should distinguish:

α_A = conversion of acrylate functionality

and

α_E = conversion of epoxy functionality.

After the first cure:

$\alpha_{A,1}$

$\alpha_{E,1}$

and after the second cure:

$\alpha_{A,2}$

$\alpha_{E,2}$

The changes:

$$\Delta\alpha_A = \alpha_{A,2} - \alpha_{A,1}$$

$$\Delta\alpha_E = \alpha_{E,2} - \alpha_{E,1}$$

reveal what the secondary treatment actually accomplished.

This may be measured by appropriately validated FTIR, Raman, DSC or complementary chemical methods depending on the chemistry.

Reporting only final hardness or modulus obscures the chemical origin of the change.

13. Stage-resolved qualification framework

A robust dual-cure material should be characterised as a sequence of states.

Table 1. Minimum qualification architecture

Variable	Liquid	After Cure 1	After Cure 2	Why it matters
Viscosity	Required	n/a	n/a	Printing and recoating
Reactive-group conversion A	baseline	Required	Required	Quantifies first network
Reactive-group conversion B	baseline	Required	Required	Tests latency and secondary cure
Dimensions	n/a	Required	Required	Separates print error from secondary-cure change
Mass	Required where relevant	Required	Required	Detects volatilisation/extraction
Modulus	n/a	Required	Required	Intermediate versus final state
Strength	n/a	Optional	Required	Final performance
Tg / DMA response	n/a	Useful	Required	Network-state development
Interlayer response	n/a	Useful	Required	Tests interface reinforcement
Morphology	baseline	Useful	Required	Detects phase evolution
Residual reactive species	baseline	Useful	Required where relevant	Chemical completion
Ageing stability	Required	application-specific	Required	Storage and service stability

The table deliberately avoids a single pass/fail value.

Dual-cure qualification is application-specific.

14. A proposed property-homogenisation descriptor

Where the purpose of Cure 2 is to reduce spatial property gradients, the result should be quantified rather than described qualitatively.

For measurements of a property **P** at n locations through a part, a simple proposed engineering descriptor is:

$$H_P = 1 - CV(P)$$

where **CV(P)** is the coefficient of variation of the measured property across the defined sampling positions.

An increase:

$$H_{P,2} > H_{P,1}$$

would indicate greater spatial uniformity after Cure 2.

This is **not a standardised materials metric** and should not replace uncertainty analysis. It is proposed here solely as a compact way to express whether a secondary cure has homogenised the selected measured property.

More importantly, the mean and distribution must always be reported together.

A perfectly homogeneous material with inadequate strength is not a successful outcome.

15. Failure modes specific to dual cure

Dual-cure formulations introduce failure modes not present, or less prominent, in ordinary single-network systems.

Premature secondary reaction

Consequences:

- shelf-life reduction;
- viscosity drift;
- loss of latency;
- uncontrolled vat-state evolution.

Insufficient Stage-1 network

Consequences:

- print collapse;
- deformation during washing;
- dimensional instability before secondary cure.

Excessive Stage-1 conversion

Consequences:

- reduced mobility for the second reaction;
- suppressed interpenetration;
- increased residual stress;
- poor secondary-network development.

Incomplete Stage-2 activation

Consequences:

- residual reactive functionality;
- weak spatial zones;
- incomplete development of thermal or mechanical properties.

Reaction-induced phase separation

Consequences may be beneficial or detrimental depending on scale and morphology.

Uncontrolled phase separation can produce:

- haze;

- local brittleness;
- inconsistent modulus;
- microstructural defects.

Excessive Stage-2 shrinkage

Consequences:

- dimensional drift;
- warpage;
- internal stress;
- interface failure.

The optimal first cure is therefore not necessarily the maximum first-stage conversion.

It is the cure state that provides adequate printability while preserving the intended secondary reaction.

16. Relationship to conventional post-curing

The distinction can be summarised as follows.

Table 2. Conventional post-cure versus engineered dual cure

Characteristic	Conventional post-cure	Engineered dual cure
Primary objective	Increase conversion of printed network	Transform intermediate network into a second defined state
Second chemistry required	No	Normally yes, or an independently activated second network-forming pathway
Intermediate state intentionally designed	Not necessarily	Yes
New network formation	Usually limited	Often central
Reaction orthogonality	Not required	Important
Latent second reaction	Not required	Usually required
Potential IPN formation	Not intrinsic	Common architecture
Spatial property programming	Limited	Possible with orthogonal stimuli
Stage-specific characterisation	Useful	Essential

This boundary should be preserved to prevent the term **dual cure** from becoming a generic synonym for “post-cured resin”.

17. Relationship to other 3Dresyns Engineering Reviews

ER-59 is intentionally restricted to **reaction-sequence and network-state engineering**.

It does not replace:

- thermal-property qualification;
- conversion metrology;

- residual-stress and warpage analysis;
- multimaterial-interface qualification;
- self-healing or vitrimer repair analysis.

Those topics intersect with dual curing but answer different questions.

The specific question addressed here is:

What becomes possible when geometry formation and final network formation are deliberately separated into independently controlled curing stages?

This scope boundary is necessary to prevent the review from becoming a general post-processing paper.

18. 3Dresyns implementation context

Commercial material documentation must remain separate from the independent literature used above.

One current 3Dresyns formulation component relevant to the design space is **3D-ADD AA3, Adhesive & Interfacial Promoter for Difficult Surfaces** [M1a, M1b].

The current manufacturer documentation describes AA3 as an adhesion-promoting additive with vitrimeric catalytic functionality intended for advanced photopolymer formulations. It is described as compatible with radical, hybrid and dual-cure systems and as supporting dynamic network exchange in thermally activated vitrimeric systems.

This is relevant to the present review as an **implementation example of a formulation component capable of participating in advanced hybrid or dynamically reconfigurable network architectures**.

It should not be interpreted as evidence that:

- AA3 by itself creates a dual-cure resin;
- every host resin becomes vitrimeric after addition;
- a particular secondary-cure mechanism is obtained without formulation development;
- literature results obtained with unrelated acrylate/epoxy systems transfer to a 3Dresyns formulation.

AA3 is an additive, not a standalone printable material, and the final cure sequence, catalyst level, network chemistry, print conditions and secondary treatment require formulation-specific validation. [M1a, M1b]

This separation between independent scientific evidence and manufacturer implementation examples should be retained in any published version.

19. Design rules

The reviewed evidence supports several practical design principles.

Rule 1. Cure 1 should be sufficient, not maximal.

The first network must retain the geometry and survive handling while preserving the chemistry and mobility required for Cure 2.

Rule 2. Cure 2 must add a defined function.

If the second operation merely continues the first photopolymerisation, the material should normally be described as post-cured rather than dual-cured.

Rule 3. Orthogonality must be measured.

Different initiators, temperatures or wavelengths do not prove independent reaction control.

Rule 4. Characterise both material states.

Green/intermediate and final properties are both technologically relevant.

Rule 5. Measure conversion by reactive functionality.

A single global cure percentage is inadequate for a multi-reaction network.

Rule 6. Treat morphology as a process variable.

Cure order and delay can influence IPN development and phase separation even at constant composition.

Rule 7. Revalidate dimensions after Cure 2.

The first geometrically correct state is not necessarily the final geometrically correct state.

Rule 8. Distinguish bulk strengthening from interlayer strengthening.

Average tensile properties cannot establish elimination of layer-interface weakness.

20. Research opportunities

Several areas remain particularly valuable.

First, dual-cure systems could be designed specifically to compensate for optical conversion gradients rather than simply to increase average conversion.

Second, improved coupling of reaction kinetics and diffusion models could predict the transition from mixed to phase-separated networks.

Third, wavelength-orthogonal systems offer a route toward continuously varying network state without exchanging resin vats, provided adequate chemical orthogonality can be maintained.

Fourth, latent reactions could enable intermediate printed structures designed for assembly, deformation or bonding before final fixation.

Fifth, dynamic covalent chemistry can extend sequential curing beyond network completion toward controlled post-print topology rearrangement, repair and reprocessing. This area should nevertheless remain conceptually separated from dual cure itself: a network can be dual-cured without being dynamic, and a dynamic network does not automatically require two curing stages.

21. Limitations

The published systems reviewed here differ substantially in composition, exposure geometry, initiator chemistry, curing temperature and mechanical testing.

Reported improvements should therefore not be interpreted as universal numerical expectations for dual-cure VPP.

In particular:

- modulus gains cannot be transferred between formulations;
- dimensional stability demonstrated for one chemistry does not establish negligible secondary-cure shrinkage in another;
- dual-wavelength behaviour depends on the complete absorption and reaction environment;
- vitrimeric behaviour requires appropriate exchangeable bonds and catalytic conditions, not merely a product label or additive;
- thermal activation conditions must remain compatible with the first network and intended application.

The purpose of the review is consequently to establish the **engineering architecture and qualification logic**, not to prescribe a universal formulation.

22. Conclusions

Sequential dual curing provides a means of separating two functions that conventional vat photopolymerisation often attempts to perform simultaneously:

creation of geometry
and
creation of the final polymer network.

The first curing stage can establish a mechanically stable printed intermediate while the second can increase conversion, introduce a second network, reinforce interlayer interfaces, modify morphology or develop final thermomechanical properties.

This approach is more than conventional post-curing when the formulation contains independently controlled reactive pathways and the intermediate state is deliberately engineered.

The available literature demonstrates several distinct implementations: photo/thermal acrylate curing, sequential acrylate-epoxy network formation, thermal interlayer crosslinking, IPN development and wavelength-orthogonal radical/cationic photopolymerisation.

These systems also introduce new qualification requirements. Conversion must be resolved by chemical functionality, the intermediate and final states must both be characterised, dimensions must be checked after the secondary cure, latency must be established during storage and printing, and final network morphology cannot be inferred from starting composition.

The central materials principle is therefore:

In sequential dual-cure VPP, printing defines the first material state, not necessarily the final material.

This decoupling creates an additional degree of freedom for photopolymer design and provides a route toward printed parts whose final properties are not constrained exclusively by the photochemical conditions required to generate their geometry.

References

- [1] Fernández-Francos, X.; Konuray, O.; Ramis, X.; Serra, À.; De la Flor, S. **Enhancement of 3D-Printable Materials by Dual-Curing Procedures.** *Materials* **2021**, *14*, 107. DOI: [10.3390/ma14010107](https://doi.org/10.3390/ma14010107).
- [2] Uzcategui, A. C.; Muralidharan, A.; Ferguson, V. L.; Bryant, S. J.; McLeod, R. R. **Understanding and Improving Mechanical Properties in 3D Printed Parts Using a Dual-Cure Acrylate-Based Resin for Stereolithography.** *Advanced Engineering Materials* **2018**, *20*, 1800876. DOI: [10.1002/adem.201800876](https://doi.org/10.1002/adem.201800876).
- [3] Konuray, O.; Di Donato, F.; Sangermano, M.; Bonada, J.; Tercjak, A.; Fernández-Francos, X.; Serra, À.; Ramis, X. **Dual-curable stereolithography resins for superior thermomechanical properties.** *Express Polymer Letters* **2020**, *14*, 881–894. DOI: [10.3144/expresspolymlett.2020.72](https://doi.org/10.3144/expresspolymlett.2020.72).
- [4] Konuray, O.; Morancho, J. M.; Fernández-Francos, X.; García-Alvarez, M.; Ramis, X. **Curing kinetics of dually-processed acrylate-epoxy 3D printing resins.** *Thermochimica Acta* **2021**, *701*, 178963. DOI: [10.1016/j.tca.2021.178963](https://doi.org/10.1016/j.tca.2021.178963).
- [5] Konuray, O.; Altet, A.; Bonada, J.; Tercjak, A.; Fernández-Francos, X.; Ramis, X. **Epoxy Doped, Nano-scale Phase-separated Poly-Acrylates with Potential in 3D Printing.** *Macromolecular Materials and Engineering* **2021**, *306*, 2000558. DOI: [10.1002/mame.202000558](https://doi.org/10.1002/mame.202000558).
- [6] Kim, H.; Han, S.; Seo, Y. **Novel Dual-Curing Process for a Stereolithographically Printed Part Triggers a Remarkably Improved Interlayer Adhesion and Excellent Mechanical Properties.** *Langmuir* **2020**, *36*, 9250–9258. DOI: [10.1021/acs.langmuir.0c01553](https://doi.org/10.1021/acs.langmuir.0c01553).
- [7] Cazin, I.; Plevová, K.; Alabiso, W.; Vidović, E.; Schlögl, S. **Dual-Wavelength Vat Photopolymerization 3D Printing with Hybrid Acrylate-Epoxy Resins: Influence of Resin Composition on Microstructure and Mechanical Properties.** *Advanced Engineering Materials* **2024**, *26*, 2301699. DOI: [10.1002/adem.202301699](https://doi.org/10.1002/adem.202301699).
- [8] Escribá-Flores, A.; Gaca, S.; Fernández-Francos, X.; Schlögl, S.; Fabregat-Sanjuan, A. **Development of a high-performance dual-curing vitrimeric acrylate/epoxy system for 3D printing: Analysis of thermal effect and network evolution.** *Reactive and Functional Polymers* **2025**, *217*, 106494. DOI: [10.1016/j.reactfunctpolym.2025.106494](https://doi.org/10.1016/j.reactfunctpolym.2025.106494).

Manufacturer-controlled sources

- [M1a] 3Dresyns by Resyner Technologies S.L. **3D-ADD AA3, Adhesive & Interfacial Promoter for Difficult Surfaces.** Public manufacturer product page. Accessed 22 August 2026. <https://www.3dresyns.com/products/3d-add-aa3-adhesive-interfacial-promoter-for-difficult-surfaces>
- [M1b] 3Dresyns by Resyner Technologies S.L. **Technical Datasheet: TDS_3d-add-aa3-adhesive-interfacial-promoter-for-difficult-surfaces_v1.3_August-2026.pdf.** Version 1.3, August 2026. Manufacturer-controlled source. https://cdn.shopify.com/s/files/1/0282/5616/files/TDS_3d-add-aa3-adhesive-interfacial-promoter-for-difficult-surfaces_v1.3_August-2026.pdf?v=1786807714

Product statements are implementation context and are not treated as independent evidence.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L., which develops and commercialises photopolymer materials and formulation additives. Manufacturer-controlled product information is explicitly separated from the independent scientific literature in this review.