

True Foam Photopolymers for Vat Photopolymerisation: Foaming Routes, Network Mobility and Cellular-Structure Qualification

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Statement of Significance

A vat-printed object containing designed holes is not necessarily a foam. A true polymer foam contains a dispersed gas phase created by a foaming process, and its performance depends on cell nucleation, growth, stabilization and the polymer network that arrests the evolving morphology. Recent VPP studies demonstrate three distinct routes: direct printing of a gas-liquid photocurable foam, post-print expansion using thermally expandable microspheres, and foaming of photocured dynamic networks. This review separates these routes from architected lattices/TPMS and from syntactic foams containing pre-existing hollow particles, then defines the measurements needed to qualify true foams without transferring study-specific expansion, resolution or mechanical values across formulations.

Keywords: vat photopolymerisation; polymer foam; cellular polymer; DLP; thermal expansion; thermally expandable microspheres; dynamic network; supercritical-fluid foaming; bubble stability; cellular morphology; density; compression

Abstract

Vat photopolymerisation (VPP) offers high geometric fidelity but normally produces densely crosslinked thermosets whose network mobility can oppose gas-driven expansion. Recent research has addressed this conflict by stabilising air directly in photocurable precursors, incorporating thermally expandable microspheres before printing, or designing dynamic networks that regain mobility during thermal or supercritical-fluid foaming. These strategies create genuinely cellular polymers rather than merely architected porous geometries. The engineering problem is therefore coupled: the formulation must remain optically and rheologically printable, the green or cured network must tolerate cell formation, and the resulting foam must be characterised by density, cell morphology, anisotropy and class-appropriate mechanical tests. This review proposes a route-based taxonomy and a minimum-reporting framework for true VPP foams. Values reported in individual studies are treated as formulation- and process-specific demonstrations, not universal performance limits. A separate implementation section describes the 3Dresyns thermally activated post-print foaming route as manufacturer evidence requiring formulation-specific validation.

1. Scope and evidence-selection method

This review is restricted to photocurable polymer systems in which a gas phase or an expandable inclusion creates cellular morphology during or after VPP. The core evidence set was selected from peer-reviewed studies that directly demonstrate DLP/VPP-compatible foaming, foam stabilization, post-print expansion or the mechanics of the resulting cellular polymer [1–6]. Architected lattices, TPMS structures and CAD-defined voids are used only as boundary cases because their porosity is prescribed geometrically rather than generated by foaming. Syntactic foams are also treated separately because hollow microspheres are already discrete cellular inclusions before cure [6]. Standards are cited only for the measurement domains they actually cover [S1–S3]. Manufacturer documentation is segregated from peer-reviewed evidence [M1–M2]. This note is a topic-specific Engineering Review in the 3Dresyns ER series; the shared evidence-to-decision and qualification method is defined once in RP-02, Evidence-to-Decision Qualification Framework for Vat Photopolymerisation, and is not reproduced here.

No quantitative value is transferred from one formulation to another. Reported expansion ratios, cell sizes, resolution, density, compressive strength or cyclic response are interpreted only under the chemistry, loading, geometry, exposure and thermal/foaming conditions of the source study.

2. What counts as a true foam

Table 1. Porous structures that should not be conflated.

Class	How void space is created	Primary control variables	Qualification consequence
True gas-phase foam	Gas bubbles are generated or introduced and then arrested by the polymer network.	Nucleation, gas fraction, cell growth, drainage/coalescence, cure and network mobility.	Report foam density and cell morphology in addition to printed geometry.
Thermally expandable-microsphere foam	Pre-dispersed expandable microspheres enlarge after printing under heat.	Microsphere content, dispersion, cure state, heating profile and network mobility.	Separate printed green geometry from final expanded geometry [2,3].
Architected lattice / TPMS	Void topology is encoded in CAD and reproduced by printing.	Unit cell, strut/shell dimensions, relative density and print fidelity.	Geometric porosity is not evidence of a foaming mechanism.
Syntactic foam	Pre-existing hollow particles are dispersed in a solid matrix.	Particle volume fraction, flotation/sedimentation, breakage, matrix cure and interface.	Treat as particle-filled composite; do not describe hollow particles as generated gas cells [6].

The distinction matters because the same nominal porosity can arise from entirely different physics. A lattice can be dimensionally inspected directly against CAD; a true foam additionally requires control of a transient multiphase system. In direct photocurable foams, bubble drainage and coalescence compete with exposure and network formation [1,5]. The kinetics that govern that competition - autoacceleration, diffusion limitation and the mobility loss that accompanies vitrification in multifunctional-monomer systems - are reviewed by Andrzejewska [7]; they are cited here as general photopolymerisation background and not as foam-specific evidence. In post-print expansion, the initial photopolymer network must be sufficiently coherent for printing yet sufficiently mobile, degradable or dynamically rearrangeable to permit cell growth [2–4].

3. Foaming routes compatible with VPP

3.1 Direct printing of a gas-liquid photocurable foam

Cheng, Tai and Liao developed a DLP route in which air is deliberately mixed into a photocurable precursor before printing. Their system couples a controlled foaming device with formulation measures that resist collapse during UV curing; nanoparticles and a UV absorber were used to balance foam stability and optical print control [1]. The study demonstrates that the feedstock itself can be a foam, but it also exposes the central engineering tension: a printable VPP liquid must reflow and photopolymerise predictably while a foam benefits from interfaces that resist drainage and coalescence. Tai, Alagarsamy and Liao subsequently showed a crystallisation-assisted interfacial strategy for stabilising nonaqueous photocurable foams, reinforcing the importance of interface design rather than assuming that a conventional resin can simply be aerated [5].

3.2 Post-print expansion with thermally expandable microspheres

Kwon and co-workers used DLP to print a photopolymer containing thermally expandable microspheres and then applied a thermal step to generate a lower-density foam [2]. This two-stage route decouples geometric printing from much of the expansion event, but the final part is not geometrically identical to the green print. Expansion uniformity, dimensional change, local density and mechanical response therefore belong to the post-foaming qualification, not merely to the printing qualification.

Gao and co-workers addressed the restriction imposed by dense photocrosslinking by incorporating dynamic polyurea chemistry that can temporarily increase network mobility during heating while supporting

subsequent chain extension/crosslinking [3]. The very high stretchability and expansion demonstrated in that specific material are proof of concept, not general properties of VPP foams.

3.3 Dynamic-network and supercritical-fluid foaming

Peng and co-workers combined photocuring with a dynamically crosslinked interpenetrating polyurethane/polyurea network to enable supercritical-fluid foaming of VPP-derived elastomeric structures [4]. This route makes network exchange chemistry part of the foaming mechanism itself. It broadens the design space beyond conventional irreversible acrylate networks, but also increases the number of state variables that must be reported: cure history, conditioning, foaming-fluid conditions, temperature, pressure, time and post-foaming stabilization.

4. Coupled formulation and process variables

Table 2. Variables that couple printability to foam formation.

Variable	Printing consequence	Foaming consequence	Minimum control
Viscosity / rheology	Controls recoating/reflow and suspension or bubble stability.	Affects drainage, bubble motion, microsphere flotation and cell coalescence.	Report test temperature, shear condition and relevant time dependence.
Optical attenuation	Sets cure depth, lateral cure and dimensional fidelity.	Bubbles, particles and interfaces scatter light and can alter conversion gradients.	Report wavelength, real irradiance/exposure strategy and optical additives.
Crosslink density	Provides green strength and dimensional retention.	High irreversible crosslink density can suppress expansion.	Characterise cure state before foaming; do not infer mobility from conversion alone.
Dynamic-network mobility	May preserve print fidelity at the printing state.	Can permit rearrangement and cell growth at the activation state [3,4].	Report activation temperature/time and recovery/stabilisation history.
Gas / expandable phase	Can disturb homogeneity and exposure.	Defines nucleation sites, expansion potential and cell-size distribution.	Report identity, concentration, dispersion and pre-print stability.
Thermal / pressure history	May occur after the geometric print is complete.	Controls activation, gas solubility, cell growth and final dimensions.	Record ramps, dwell times, pressure/fluid and cooling or fixation step.

5. Cellular morphology and dimensional qualification

Final foam morphology should be reported independently of the nominal CAD porosity. At minimum, apparent density should be measured on the final cellular article; ISO 845:2006 provides a method for apparent overall/core density of cellular plastics and rubbers [S1]. Microscopy or micro-computed tomography can then quantify cell-size distribution, cell shape, wall thickness, open/closed character where methodologically justified, gradients and skin/core differences. For post-print expansion, dimensional metrology should compare at least the printed pre-foaming state, the expanded state and the conditioned final state. A single global expansion ratio cannot reveal local anisotropy or skin-constrained growth.

The source literature illustrates why this separation is necessary. Directly printed foam can preserve intricate geometry under a deliberately stabilised precursor [1], whereas microsphere or dynamic-network routes intentionally alter dimensions after the first photopolymerisation stage [2,3]. Qualification must therefore distinguish print fidelity from foam-morphology fidelity.

6. Mechanical qualification must follow foam class

Mechanical results should be interpreted together with density, cell morphology, specimen orientation and conditioning. For rigid cellular plastics, ISO 844:2026 defines compressive-strength, strain and modulus procedures [S2]. For low-density flexible cellular polymeric materials, ISO 3386-1:2025 defines compression stress/strain characterization within its stated scope [S3]. These methods are not interchangeable, and neither substitutes for application-specific cyclic, impact, thermal, acoustic or damping tests.

Kwon et al. explicitly evaluated repeated compressive loading and energy dissipation in their microsphere-derived DLP foams [2]. Gao et al. and Peng et al. demonstrate that dynamic-network design can produce highly deformable elastomeric foams [3,4]. Such results support route feasibility but do not establish a universal density-property law across VPP foam chemistries.

7. Failure modes and interpretation

Table 3. Failure modes that should be separated during development.

Failure mode	Observable	Likely variables	Required response
Foam collapse before/during cure	Loss of gas fraction; large drainage zones; nonuniform cells.	Interface stability, viscosity, cure latency, gravity and recoating time.	Measure time-to-print and morphology versus residence time [1,5].
Suppressed expansion	Green part prints correctly but expands little or unevenly.	Crosslink density, activation temperature, microsphere/gas phase and network mobility.	Requalify cure state and thermal/foaming window [2–4].
Overexpansion / dimensional drift	Cell growth exceeds dimensional tolerance or distorts thin features.	Activation severity, local constraint, wall thickness and heat transfer.	Map local dimensional change, not only bulk volume.
Optical under/over-cure	Weak cell walls, blurred edges or cure gradients.	Scattering by gas/particles, absorber level, wavelength and exposure.	Rebuild working exposure conditions for the foamed formulation [1].
Phase segregation	Microspheres/fillers accumulate by height or time.	Density mismatch, viscosity, residence time and mixing.	Use controlled sampling and verify vertical/time uniformity [6].
Skin/core mismatch	Dense skin with different cell structure/mechanics from core.	Gas escape, thermal gradient, cure gradient and boundary constraint.	Report overall and core density/morphology where relevant [S1].

8. Minimum reporting framework

Table 4. Minimum information for reproducible VPP foam reporting.

Block	Minimum information	Why it matters	Claim boundary
Resin state	Matrix chemistry class, reactive components by functional role, viscosity/rheology and temperature.	Defines print and foam mobility window.	Do not infer network mobility from resin family name.
Foaming phase	Air/gas/expandable microsphere/SCF identity, concentration or fraction and preparation route.	Defines cell-generation mechanism.	Do not compare expansion ratios across different mechanisms without normalization.
Photoprocess	Wavelength, irradiance/exposure, layer strategy, cure depth or conversion control and build orientation.	Foam interfaces alter optical transport.	Printer name alone is insufficient.
Activation	Temperature/pressure/fluid,	Controls nucleation and cell	Study-specific activation windows

Block	Minimum information	Why it matters	Claim boundary
	ramps, dwell, timing relative to cure and cooling/fixation.	growth.	are not universal.
Morphology	Final density, cell-size distribution, gradients, skin/core state and anisotropy.	Defines the actual cellular material.	CAD porosity is not a substitute.
Mechanics	Foam class, specimen geometry/orientation, conditioning, density and selected test standard.	Enables meaningful comparison.	Do not compare rigid and flexible foam tests as equivalent.

9. 3Dresyns implementation examples

Manufacturer documentation is included here only as an implementation example and is not used as peer-reviewed evidence for universal foam performance.

- 3D-ADD CBA1 Bio is documented by 3Dresyns as a paste-form chemical blowing-agent route for selected compatible photopolymer systems. It is mixed into the compatible resin before printing; after printing and UV curing, a controlled thermal treatment is used to activate gas generation and post-print cellular expansion, with an activation window stated by the manufacturer in the approximate range 140-180 °C [M1]. The product name and page carry the manufacturer term "Biocompatible". That term is reproduced here only as part of the controlled product identity: this review makes no biological, toxicological or medical-device claim for the additive, for any resin it is mixed into, or for any foamed part produced from them. Biological suitability, where relevant, requires evaluation of the exact finished article for its intended contact type and duration.
- The 3Dresyns foam-material collection [M2] distinguishes two production routes: "true cellular foam" produced by chemical blowing-agent activation with subsequent thermal expansion, and directly printable elastic structures that reproduce foam-like softness without expansion. The collection states that photopolymer resins do not expand after printing unless a blowing agent is incorporated before printing and later activated by heat. Cushioning and lightweight geometries appear on that page as application descriptors rather than as a separately qualified third route; the CAD-defined lattice/TPMS class distinguished in Table 1 of this review is a taxonomic boundary drawn here, not a route asserted by the manufacturer source.
- No universal additive dosage, expansion ratio, cell size, density reduction, print-speed setting or mechanical result is asserted here. The exact base resin, CBA loading, printer, exposure, geometry, cure state and thermal profile require qualification for the intended part.

10. Conclusions

- True VPP foams must be defined by a gas-generation or gas-introduction mechanism, not by the visual presence of designed voids.
- Direct precursor foaming, thermally expandable microspheres and dynamic-network/supercritical-fluid routes solve different stability and network-mobility problems and should not be pooled as one process.
- The print state and the final foam state are separate qualification states whenever expansion occurs after photopolymerisation.
- Density, cellular morphology, dimensional change and class-appropriate mechanical testing are minimum evidence blocks; study-specific performance numbers must remain formulation- and process-specific.
- Architected lattices/TPMS and syntactic foams remain useful lightweight-material strategies, but their physics and reporting requirements differ from true gas-phase polymer foams.

Limitations

This is a literature-based engineering review, not a meta-analysis. The contemporary VPP foam literature remains small and heterogeneous, with different resin chemistries, gas-generation routes, thermal histories and mechanical tests. The review does not establish application-specific acoustic, thermal, impact, biomedical or durability performance. Manufacturer implementation examples require independent validation of the exact formulation and finished part.

Author contributions

Juan Segurolo: conceptualisation, literature synthesis, engineering interpretation, writing, review and final approval.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. Product examples are therefore segregated from the peer-reviewed evidence and are identified as manufacturer evidence.

Data availability

No new experimental dataset was generated for this review. All scientific claims derive from the cited literature and standards. Manufacturer examples derive from the cited controlled 3Dresyns documentation.

Company information

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