

Elastomeric and Rubber-Like Photopolymers for Vat Photopolymerisation: Network Design, Tear Resistance, Creep, Compression Set and Cyclic Durability

Juan Seguro

3Dresyns by Resyner Technologies S.L.

Registered tax address: General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain

VAT number: ESB24827511

Correspondence: info@3Dresyns.com · Website: ww

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Statement of Significance

Elastomeric, flexible, rubber-like and silicone-like are often used as if they were interchangeable material specifications. They are not. For vat-photopolymerised parts, a large elongation at break can coexist with poor notch tolerance, permanent set, time-dependent deformation or early cyclic failure. This review separates functional description from chemical identity and from qualification state. It links network design to printability, tear resistance, creep, stress relaxation, compression set and cyclic durability, and proposes a minimum test architecture that prevents one tensile curve, one Shore value or one visually recovered lattice from carrying claims it cannot support.

Keywords: vat photopolymerisation; elastomeric photopolymer; rubber-like; network architecture; tear resistance; creep; stress relaxation; compression set; cyclic durability; fatigue; qualification.

Abstract

Vat photopolymerisation can manufacture compliant structures with complex internal channels, thin membranes and fine features, but the formulation requirements for recoating and rapid cure compete with the long, mobile network strands needed for soft and durable elastomeric response. Primary studies from 2017 to 2026 demonstrate several routes for moderating this trade-off, including flexible urethane-acrylate segments, densely entangled networks, reversible hydrogen-bonded physical crosslinks, dynamic covalent topology and sequential or dual cure. Reported formulation-specific tensile results range from sub-megapascal moduli and very high extension to unusually high strength and toughness. These demonstrations establish a broad design space, not a universal property envelope. Tensile strength and elongation at break do not determine tear propagation, crack sensitivity, creep, stress relaxation, compression set or fatigue life. Cyclic loading curves are also conditional on strain amplitude, cycle count, recovery interval, waveform, frequency, temperature, conditioning and failure definition. This review organises elastomer qualification around five evidence blocks: monotonic tensile response; tear and notch sensitivity; time-dependent set and relaxation; cyclic durability and fatigue; and geometry-representative component testing. Process state, build orientation, washing, drying, post-cure and ageing are treated as controlled variables. True polysiloxane and silicone chemistry are excluded and assigned to ER-102. Under the manufacturer declaration used here, 3Dresyns silicone-like products are silicone-free photopolymers with silicone-like functional behaviour, not direct silicone materials; composition-to-silicone comparisons and thermal-service limits remain outside ER-101. The result is a provider-neutral qualification framework rather than a product ranking, formulation recipe or intended-use approval.

1. Scope and boundaries

ER-101 concerns photocurable, vat-printable materials intended to behave as elastomers or rubber-like solids after processing. It asks which network architectures can deliver compliance and recovery, what the literature actually demonstrates, and which measurements are still needed before a printed part can be qualified for repeated deformation, sealing, cushioning, wearable contact or soft-machine service. The review covers acrylate, methacrylate, polyurethane-acrylate, poly(urethane-urea), entangled and dual-curable systems when their cured response is elastomeric or rubber-like.

The scope is deliberately narrower than adjacent Engineering Reviews. ER-13 owns self-healing and interlayer repair; ER-24 owns device-level soft-robotics actuation; ER-39 owns the general fatigue and time-dependent-deformation gap for vat-printed thermosets; ER-68 to ER-70 own toughening, fatigue-crack growth and fracture toughness; ER-73 owns interlayer cohesion and anisotropy; and ER-90 owns frequency- and temperature-dependent damping. ER-101 uses those quantities only to define the elastomer-specific qualification stack and does not reopen their full scopes [C1–C8].

True silicone or polysiloxane materials, hydrosilylation chemistry, condensation cure, silicone double networks and silicone-specific temperature or chemical performance are excluded. They are assigned prospectively to ER-102. The

word silicone-like is therefore treated only as a functional or commercial descriptor. It must not be interpreted as evidence of siloxane composition, silicone equivalence or a universal thermal-use range.

2. Rubber-like is a functional description, not a chemical identity

An elastomeric response normally implies large reversible deformation on the timescale and temperature of interest, but the boundary is operational. A cured photopolymer can feel soft in a short manual bend and still accumulate set under a sustained compressive load. It can show high extension in an unnotched tensile specimen and tear rapidly from a sharp feature. It can recover its overall shape after one cycle yet soften, heat or crack during thousands of cycles. A functional label therefore needs a declared test condition and acceptance criterion.

Descriptor or metric	What it can support	What it does not establish
Shore hardness	Indentation response under the stated scale, time and conditioning	Tear strength, tensile modulus, set, creep, fatigue or seal life
Tensile modulus	Stiffness over the stated strain interval and rate	Large-strain recovery, crack tolerance or compression behaviour
Elongation at break	Extension at rupture for a defined unnotched specimen	Elastic recovery, low hysteresis, tear resistance or cycle life
Tensile strength	Maximum engineering stress under a stated method	Fracture energy, flaw tolerance, interface strength or retained performance
Toughness from stress-strain area	Energy per volume to tensile rupture in that specimen	Tear propagation, fatigue-crack growth or component impact survival
Cyclic hysteresis loop	Energy loss and path dependence for stated cycles and amplitudes	Long-term fatigue, steady-state damping or absence of damage
Visual shape recovery	Macroscopic return after a declared recovery interval	Recovered force, dimensions, modulus, seal pressure or microcrack state

Table 1. Functional descriptors and their evidential limits. Each claim remains conditional on specimen, process state, environment and method.

3. The printability–mechanics trade-off

Projection-based VPP favours formulations that flow or recoat within the machine cycle, absorb the selected spectrum predictably and gel fast enough to preserve each layer. Elastomeric performance, by contrast, often benefits from high-molar-mass oligomers, long flexible strands, low effective crosslink density, strong reversible associations or chain entanglements. Those features can increase viscosity, slow transport and cure, or amplify sensitivity to post-cure. Printability and final mechanics therefore share the same formulation variables but do not necessarily share the same optimum.

Patel et al. showed in 2017 that mixtures of epoxy aliphatic acrylate and aliphatic urethane diacrylate could produce DLP-printable systems with formulation-specific elongation reported up to about 1100% [1]. Song et al. later treated viscosity, cure time, tensile modulus and elongation as simultaneous optimisation targets. Their selected formulation combined approximately 2500 mPa·s viscosity with elongation exceeding 600%, but the paper also showed that post-cure dose, temperature and strain rate changed the measured response [6]. These studies support multi-objective formulation design. They do not establish that high extension is automatically retained across printers, temperatures, geometries or duty cycles.

A useful development workflow therefore separates screening from release. Mold-cured or bulk-cured specimens can identify broad composition trends, while printed specimens are needed to capture interlayer boundaries, optical gradients and post-processing effects. Song et al. reported consistent property ranking between selected mold-cured and printed formulations but also observed absolute shifts attributed to printing-specific microstructure [6]. A screening correlation is not a waiver from printed-state qualification.

4. Network-design routes

4.1 Long compliant strands and moderated effective crosslink density

Long flexible network strands can reduce modulus and delay finite-chain extensibility. Urethane-acrylate oligomers and flexible reactive diluents are common routes, but lowering crosslink density can also increase sol fraction, creep, tack, oxygen sensitivity or dimensional drift if conversion and extraction are not controlled. The relevant design quantity is not nominal functionality alone. Effective strand length, intramolecular reaction, dangling chains, heterogeneity and phase organisation all influence the load-bearing network.

4.2 Entanglement as a load-transfer mechanism

Dhand et al. combined light and dark polymerisation to form densely entangled printed networks and reported four- to seven-fold higher extension energies than traditional DLP comparators across hydrogel and elastomer examples [2]. This is a strong formulation-specific demonstration. It does not convert entanglement into a formulation-independent guarantee of compression set, heat resistance or fatigue life.

4.3 Reversible physical associations

Hydrogen-bonded urethane or urea groups can act as reversible physical crosslinks and sacrificial energy-dissipation sites. Yang et al. reported a dual-crosslinked poly(urethane-urea) system with 28.30 ± 1.10 MPa tensile strength, recovery strain of approximately 300% and fracture energy of 22.90 ± 4.20 kJ m⁻² [4]. Shi et al. reported 20.7 MPa strength and 326% elongation for a urea-containing photocurable formulation and attributed the response to physical crosslinking and energy dissipation [7]. Reversible bonds can raise toughness and apparent recovery, but their lifetime is temperature-, rate- and environment-dependent. Water, solvents, heat and long dwell times may change association strength and therefore must be included in qualification.

4.4 Dynamic topology and staged cure

Fang et al. reported a photo-printable elastomer with 94.6 MPa tensile strength and 310.4 MJ m⁻³ toughness, attributing the performance to dynamic covalent topology reconfiguration, hierarchical hydrogen bonding, microphase separation and an interpenetrating architecture [3]. Zhao et al. used a dual-curable polyurethane-acrylate route involving ionic association and thermal cure; the reported formulation reached 15.8 MPa tensile strength, 499.1% elongation and 50 µm printed resolution, with high fatigue resistance described for the tested conditions [5]. Such routes can decouple green strength from final network development. They also make the cure schedule, thermal history and conversion sequence part of the material identity.

Network route	Demonstrated opportunity	Residual qualification risk
Long flexible strands / lower effective crosslink density	Softness and high extension	Creep, sol fraction, tack, set and dimensional drift
Dense entanglement	Higher extension energy, softness and flaw tolerance	Process-time dependence, incomplete transfer to compression or thermal service
Hydrogen-bonded physical crosslinks	Strengthening, dissipation and recovery	Rate, temperature, humidity and solvent sensitivity
Dynamic covalent topology	Reconfiguration, high strength and toughness	Kinetic window, ageing and possible conflict with dimensional stability
Sequential or dual cure	Printable green state followed by stronger final network	Schedule dependence, cure gradients and batch/process reproducibility
Architected lattice	Tailored force-displacement and energy absorption	Geometry-dominated result; not an intrinsic resin property

Table 2. Network-design routes and the qualification questions that remain after a successful demonstration.

5. Why a tensile curve is necessary but insufficient

Monotonic tension is a necessary first block because it establishes stiffness, yield or strain-hardening behaviour, maximum stress, extension and failure location under a controlled rate. ISO 37:2024 provides a rubber-specific tensile framework, while plastics methods may be retained where justified by material class and legacy comparability [S1]. The selected method, specimen type, thickness, orientation, strain measurement and conditioning must be stated. Crosshead displacement should not be silently equated with local gauge strain at large deformation.

The tensile result should be interpreted as a curve, not only as two endpoints. Initial or secant modulus, onset of nonlinearity, strain softening, strain hardening, residual strain after unloading and rupture location can expose different network limitations. Rate sweeps and temperature sweeps are especially important when reversible associations or a glass transition lie near the service window. Song et al. observed modulus and elongation changes with rate and temperature, including pronounced softening and reduced extension at elevated temperature [6]. This is why a room-temperature catalogue value cannot define a universal service envelope.

6. Tear resistance, notch sensitivity and crack-controlled failure

Many elastomeric components contain edges, holes, membrane corners, support-removal marks, layer steps or surface defects. These features convert a nominally uniform load into a local crack-driving field. An unnotched tensile specimen can therefore rank formulations differently from a trouser, angle or crescent tear specimen. ISO 34-1:2022 provides defined tear configurations for vulcanised or thermoplastic rubber and illustrates why the specimen and cut geometry must be reported [S2].

Tear force, tear strength, tensile toughness and fracture energy are related but non-interchangeable quantities. A tear result may depend on crack path, specimen thickness, cut quality, orientation, test rate and whether the crack follows an interlayer or bulk path. Huang et al. explicitly investigated entanglement–crosslinking synergy for tear resistance in photocurable printed elastomers [8]. That focus is important because a network designed for high unnotched extension may still fail from a nick if local energy dissipation and crack blunting are insufficient.

For VPP, tear qualification should include at least two build orientations when layer alignment can change the crack path, microscopic or photographic confirmation of the initiation site, and a record of surface finishing. If the application contains a critical notch or membrane corner, a geometry-representative test should supplement standard coupons. ER-69 and ER-70 remain the controlling references for fatigue-crack growth and fracture-toughness methodology; ER-101 does not replace them [C5,C6].

7. Creep, stress relaxation and compression set

Time-dependent deformation is often the decisive property for gaskets, clamps, wearables, grippers and cushioning parts. Creep asks how strain increases under a maintained load. Stress relaxation asks how force falls under a maintained deformation. Set asks how much deformation remains after a prescribed load or displacement and recovery interval. These experiments address different boundary conditions and cannot be inferred from each other.

ISO 2285:2019 covers tension set, elongation and creep under defined tensile loading; ISO 3384-1:2024 covers stress relaxation in compression at constant temperature; ISO 815-1:2019 covers compression set at ambient or elevated temperature; and ISO 7743:2017 covers compression stress–strain response [S3–S6]. A valid report needs the applied strain or stress, dwell time, temperature, specimen geometry, restraint, recovery time, measurement timing and any thermal preconditioning. Compression set reported without these fields is not transferable.

Photocurable networks create additional state variables. Continued dark reaction or post-cure can reduce residual species and increase network density, but may also increase modulus or reduce extension. Solvent washing can extract unreacted species or cause temporary swelling. A specimen tested immediately after post-cure may differ from one equilibrated for several days. Reversible hydrogen bonds can sustain short-duration loads yet relax during longer dwell or at higher temperature. Release criteria should therefore be linked to the actual dwell and recovery times of the application, not only to a convenient laboratory interval.

8. Cyclic durability, hysteresis and fatigue

A cyclic loading–unloading curve contains at least four separate signals: hysteretic energy loss, residual strain, stress softening and progressive damage. Their evolution with cycle number is more informative than a single loop. The first cycle may include seating, network rearrangement and Mullins-type softening; later cycles may approach a repeatable state or may continue to degrade. Preconditioning cycles should be declared rather than silently removed from the result.

Song et al. reported 100 tensile cycles at 200% strain with residual strain stabilising after early cycles, while specimens at 250% strain failed at approximately 30 cycles under their stated conditions [6]. This result demonstrates a strong amplitude dependence and shows why the phrase fatigue resistant must always be tied to amplitude, waveform, frequency, temperature and failure definition. Likewise, the cyclic compression of a printed gyroid in the same paper - 100 cycles at 60% strain, with a stable compressive modulus - is a component-architecture result. It cannot be interpreted as the intrinsic compression set of the solid resin.

ISO 6943:2017 provides a tension-fatigue method for vulcanised rubber. ISO 4666-4:2018 addresses resistance to fatigue and temperature rise in constant-stress flexometer testing, while ISO 4664-1:2022 gives general guidance for dynamic-property measurement [S7–S9]. Applicability to a photocured material must be justified and deviations recorded. A useful fatigue programme includes strain- or stress-controlled loading, multiple amplitudes, run-outs, specimen survival distribution, failure location, stiffness retention, temperature monitoring and a declared cycle-count censoring rule.

9. Process and conditioning state are part of the specimen

For VPP elastomers, the specimen is not defined by resin name and geometry alone. Optical spectrum, irradiance, exposure per layer, cure depth, layer thickness, orientation, build location and support strategy affect conversion and local continuity. Washing time, solvent, agitation, drying, post-cure spectrum, dose, temperature and delay before testing can alter residual content and network state. Storage and ageing can continue those changes.

Anisotropy may appear as a strength difference, but for elastomers it can also appear as a crack-path difference, residual-strain difference or fatigue-life difference. ER-73 owns the general interlayer-cohesion scope [C7]. ER-101 requires the same state variables to be carried into tear, set and cyclic tests. If a study reports only one orientation or one post-cure condition, its conclusion should remain bounded to that state.

State block	Minimum fields	Why it matters for elastomers
Formulation and batch	Code, batch, age, storage, mixing and composition disclosure level	Viscosity, cure, association and network density can drift
Printer and optics	Machine, spectrum, calibration location, layer thickness and exposure strategy	Controls gelation, cure gradients and interlayer continuity
Geometry and orientation	Specimen type, dimensions, build angle, location, supports and surface finishing	Changes strain field, notch population and crack path
Cleaning and drying	Solvent, time, agitation, temperature, drying and delay	Extraction or swelling changes mass, dimensions and modulus
Post-cure	Spectrum, irradiance/dose, time, temperature and fixture	Changes conversion, crosslink density, residuals and set
Conditioning	Temperature, humidity/medium, duration and equilibrium criterion	Reversible bonds and viscoelastic response are environment-dependent
Mechanical protocol	Standard/edition, rate or frequency, amplitude, waveform, cycles and failure rule	Defines the timescale and damage history being measured

Table 3. Minimum state description for transferable elastomeric VPP results.

10. Coupon properties and architected-part response

Lattices, honeycombs and gyroids can transform a solid material response into a tailored component response. Cell topology, relative density, wall thickness, buckling mode and contact strongly influence force–displacement behaviour. Thirunavukkarasu et al. studied mechanically robust elastomeric lattices inspired by hierarchical structures [9], while Shi et al. demonstrated energy absorption with printed honeycomb-like parts [7]. These studies support architecture-enabled performance. They do not make the architecture result an intrinsic resin property.

The qualification chain should therefore proceed in two stages. Material coupons establish the solid network response under defined states. Representative parts then establish the interaction between material, geometry, interfaces and load path. A lattice that recovers its height after compression may still lose peak force, dissipate a different amount of energy, develop local cracks or change dimensions. Component acceptance should include the functional quantity that matters, such as retained sealing force, blocked force, pressure stability or energy absorption, rather than visual recovery alone.

11. 3Dresyns implementation boundary

The 3Dresyns public collection uses silicone-like to organise two elastomeric hardness routes and explicitly states that they are not direct silicone materials [M1]. For this review, the author further declares that these products are silicone-free photopolymer formulations. That statement identifies the intended composition boundary; it is not an independent chemical analysis, a disclosure of proprietary composition or evidence of equivalence to polysiloxane elastomers.

Accordingly, ER-101 does not infer universal tear strength, compression set, fatigue life, chemical resistance or temperature resistance for any 3Dresyns product. Product selection remains conditional on the current technical documentation, printer calibration, geometry and intended duty. ER-102 will examine which silicone-like functions can be reproduced by silicone-free networks, where the comparison fails, and why the thermal-resistance range is generally lower than that of appropriately selected silicone systems. No direct replacement claim is made here.

12. Minimum qualification architecture

- Freeze the material-process-workflow state: formulation and batch, printer and optical settings, geometry, orientation, washing, drying, post-cure, conditioning and test age.
- Measure monotonic tensile response under a declared rubber- or polymer-appropriate standard, including the full curve, strain method and failure location.
- Add a tear or notch-sensitive test when the part contains edges, holes, membranes, support marks or other crack initiators; report crack path and orientation.
- Measure creep or stress relaxation under the actual load-control mode of the application and for a duration sufficient to resolve the relevant timescale.
- Measure compression or tension set with specified deformation, temperature, dwell and recovery interval when retained geometry or force matters.
- Run cyclic tests at multiple amplitudes, with declared waveform, frequency, preconditioning, temperature, cycle count, run-out and failure criterion.
- Track retained properties, not only survival: stiffness or force, residual strain, hysteresis, temperature rise, dimensions and failure location.
- Use geometry-representative component tests after coupon screening and define the functional acceptance quantity for the actual part.
- Repeat critical tests after relevant environmental conditioning, including heat, humidity, fluid exposure, UV or ageing where applicable.

- Keep intended-use, biocompatibility, regulatory and safety qualification separate from mechanical screening; none follows from the label rubber-like.

13. Failure-mode and interpretation matrix

Observed result	Plausible mechanisms	Required next check
High elongation but early tear	Notch sensitivity, weak interlayer path, surface defect or insufficient crack dissipation	Standard tear test, orientation comparison, crack-path inspection
Good first-cycle recovery but growing set	Network rearrangement, viscoelastic flow, incomplete cure or damage accumulation	Multi-cycle residual strain, recovery-time sweep, conversion and conditioning audit
Compression force decays at fixed deflection	Stress relaxation, temperature rise, association exchange or local buckling	Compression relaxation on solid coupon plus component test
Low hysteresis but short fatigue life	Limited dissipation near a flaw, high local stress or crack-growth sensitivity	Amplitude–life programme and failure-location analysis
High hysteresis and heating	Viscoelastic loss, sacrificial-bond cycling, friction or damage	Frequency/temperature sweep, temperature monitoring and retained modulus
Post-cure increases strength but reduces extension	Higher conversion or crosslink density and shorter effective strands	Dose series with gel fraction, DMA and tear/set measurements
Lattice recovers but coupon set is poor	Geometry-driven recovery or elastic instability masks material set	Solid compression-set test and retained component force
Batch or printer transfer changes performance	Viscosity, spectral mismatch, exposure, washing or post-cure state changed	State-variable audit and controlled transfer experiment

Table 4. Failure-mode matrix for deciding which additional evidence is needed. Mechanisms are hypotheses until tested.

14. Research and standardisation priorities

- Round-robin comparison of VPP elastomer tensile, tear, set and cyclic results using a shared material-process-workflow state description.
- Long-duration creep, stress-relaxation and compression-set datasets across temperature and humidity rather than short room-temperature demonstrations alone.
- Amplitude–frequency–temperature fatigue maps with run-outs, failure distributions and crack-location reporting for printed elastomers.
- Direct comparison between unnotched tensile toughness, standard tear, fracture energy and fatigue-crack growth in the same printed network state.
- Validated transfer rules from mold-cured screening to printed parts, including interlayer, surface and conversion-gradient effects.
- Separation of material and architecture contributions in cyclic compression, energy absorption and visual recovery experiments.
- Open reporting of post-cure dose, specimen age and recovery interval, which are frequently omitted despite controlling the measured response.
- Clear nomenclature distinguishing silicone, silicone-like, rubber-like and elastomeric photopolymers, with composition claims separated from functional similarity.

15. Conclusions

Vat-photopolymerised elastomers occupy a broad and rapidly expanding design space. Flexible network strands, entanglement, reversible physical associations, dynamic topology and staged cure can produce combinations of softness, extension, strength and toughness that were difficult to access in earlier printable resins. The strongest recent studies demonstrate that printability and mechanical performance can be partly decoupled, but every reported value remains formulation-, process-, specimen- and test-specific.

The controlling qualification conclusion is simple: elongation at break is not elastic recovery, tensile toughness is not tear resistance, a cyclic loop is not fatigue life, and a recovering lattice is not a compression-set result. A defensible elastomer release requires monotonic, notch-sensitive, time-dependent, cyclic and component-level evidence under a frozen material-process-workflow state. The functional term rubber-like should describe a bounded behaviour, not substitute for chemical identity or qualification.

ER-101 therefore closes with a strict boundary. It addresses silicone-free and other non-silicone photocurable networks that deliver elastomeric or rubber-like behaviour. True silicone chemistry and the controlled comparison between silicone and silicone-like photopolymers belong to ER-102. This separation protects both the scientific interpretation and the manufacturer statement that 3Dresyns silicone-like products are not direct silicone materials.

Limitations

This paper is a qualitative engineering review, not a systematic meta-analysis. The cited studies use different chemistries, printers, specimen geometries, cure schedules, rates, temperatures and definitions, so reported numerical values are not pooled or ranked. Several recent papers provide strong demonstrations but limited long-duration creep, compression-set or fatigue-life evidence. Standards written for vulcanised or thermoplastic rubber can provide useful method anchors, but applicability and deviations must be justified for photocured networks. No proprietary formulation data, independent product chemistry, intended-use qualification or regulatory assessment are presented.

Author contributions

Juan Seguro: conceptualisation, evidence synthesis, boundary definition, engineering interpretation, manuscript preparation and final author verification.

Competing interests

The author is founder and CEO of 3Dresyns by Resyner Technologies S.L. Manufacturer sources are segregated from independent scientific evidence. No comparative product recommendation is made.

Data availability

No new experimental dataset was generated for this review. Scientific statements derive from the cited primary literature and standards. The review package includes a QA report and a source-ledger summary for independent full-manuscript review.

Company information

3Dresyns by Resyner Technologies S.L. · General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain · VAT ESB24827511 · info@3Dresyns.com · www.3Dresyns.com

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Version note

v0.3 records the independent focused delta verdict APPROVE and creates the released document without changing accepted science. The v0.2 content, references, tables and corpus boundaries are retained. Juan Segurola remains the sole author string, without an academic-degree suffix