

Mechanical Recycling and Reuse of Cured Photopolymer Waste: Size Reduction, Resin Reincorporation and Requalification

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Statement of Significance

Mechanical recycling of a cured photopolymer does not reverse thermoset network formation and does not restore the original liquid resin. The experimentally demonstrated route is different: cured material is mechanically reduced to particles and intentionally reincorporated into a liquid photopolymer, creating a particulate composite and therefore a new formulation state. The recycled fraction can change rheology, recoating, optical transport, cure, interface formation and final properties even when the source waste came from the same nominal resin.

ER-183 defines the evidence required to qualify that new state. It separates feedstock identity, size reduction, particle characterisation, dispersion, optical and rheological consequences, printing, post-processing and property verification. It also separates technical reuse from chemical recycling, closed-loop recovery and environmental-superiority claims. No published recycled fraction, particle size or retained-property result is treated as a universal operating limit.

Keywords: *vat photopolymerisation; mechanical recycling; cured thermoset waste; cryomilling; recycled particles; DLP; particulate composite; rheology; optical attenuation; requalification*

Abstract

Direct primary studies have demonstrated physical reuse of cured vat-photopolymerisation thermosets by mechanically reducing printed material to particles and reincorporating those particles into fresh photocurable resin [1,2]. A broader DLP study incorporating cryomilled polymer wastes, including previously 3D-printed thermosets, identifies two coupled process consequences of the particulate feed: increased viscosity and UV-light blocking [3]. These demonstrations establish technical feasibility within specific material, particle, loading and process conditions. They do not establish that cured thermoset waste becomes virgin resin again, that arbitrary production scrap can be mixed into a commercial resin, or that any published recycle fraction transfers to a different formulation.

ER-183 treats every recycled-particle addition as a new formulation state that must be requalified. The controlled chain is feedstock identity -> size reduction -> particle state -> dispersion and rheology -> optical transport and cure -> particle-matrix interface -> printing and post-processing -> final properties -> application-specific disposition. Direct VPP rheology and DLP composite-interface studies provide additional mechanism-level support for why particle fraction, size distribution, shear history, temperature and interfacial state must be controlled [4,5]. The series evidence framework requires claims to remain tied to the material, machine, exposure, geometry, post-processing and measurement state actually tested [6]. The review therefore proposes a qualification architecture rather than a universal recycling recipe.

1. Scope, terminology and ownership

ER-183 addresses mechanical size reduction and physical reincorporation of ordinary cured photopolymer thermoset waste. The defining operation is not cleavage of the cured network. The network remains as a solid particle and is introduced into a fresh liquid matrix. The resulting material is therefore a particle-filled photocurable formulation whose state differs from the neat resin even when the particle source and matrix share the same commercial identity.

The term recycled feed in this review means a deliberately identified cured material that has undergone a controlled mechanical preparation route. It does not include unidentified mixed waste, contaminated floor sweepings, partially cured vat sludge, solvent-laden washing residues or arbitrary aged resin. Those materials have additional identity and contamination problems that are not closed merely by grinding them.

ER-017 retains life-cycle assessment and environmental-superiority claims. ER-063 and ER-074 retain dynamic or chemically reprocessable network mechanisms. ER-111 to ER-113 retain designed chemical cleavage, exchange and recovery routes. ER-178 retains solvent, wash-water and contaminated-waste management. ER-183 owns the engineering evidence required when cured thermoset material is intentionally converted into a particulate feed and physically reincorporated.

Route	Physical state after operation	Permitted interpretation	Prohibited inference
Mechanical reuse	Cured thermoset particles in a matrix	A controlled particulate feed can be qualified in a new photocurable formulation	Virgin resin restoration
Chemical recycling	Recovered molecular or oligomeric species	Outside ER-183	Closed-loop chemical recovery from mechanical milling

Route	Physical state after operation	Permitted interpretation	Prohibited inference
Reuse of uncured resin	Uncured or recovered liquid formulation	Outside ER-183	Equivalence to mechanically recycled cured solids
Waste management	Waste, solvent or wash-water stream	Outside ER-183	Product qualification

2. What the direct evidence demonstrates

Maines et al. directly studied mechanical recycling of 3D-printed thermosets for reuse in vat photopolymerisation [1]. The official publisher record describes cured parts being cryomilled to powder and reincorporated into liquid resin. The study reports more than one material system and investigates the interaction of recycled particles with the liquid and subsequently cured matrix. This is direct evidence that a cured thermoset need not be chemically depolymerised before it can serve as a controlled particulate constituent in a new VPP formulation.

Rooney et al. independently demonstrated cured DLP epoxy-acrylate particles used as fillers in fresh epoxy photopolymer and evaluated mechanical and rheological response [2]. Their study also shows why a single statement such as recycled resin is insufficient: particle size and loading were experimental variables, and different combinations did not behave identically.

Gholami et al. broaden the direct AM evidence by cryomilling several polymer waste streams, including 3D-printed thermosets, and incorporating the powders into a DLP photocurable resin [3]. Their work directly identifies increased viscosity and UV-light blocking as process challenges introduced by the solid particles. The exact heated-vat temperature, particle loading, dual-cure formulation and property changes belong to their system. ER-183 transfers the mechanism and the need for qualification, not those numerical settings.

Together these studies establish feasibility and the principal qualification problem. They do not establish universal recyclability of all cured photopolymers, unlimited repeated cycling, unrestricted mixing of waste identities, or unchanged performance at a selected recycle fraction.

3. A mechanically recycled thermoset is a particulate feedstock

The correct material model after size reduction is a particulate composite, not a restored molecular resin. That distinction controls almost every downstream measurement. The particles possess a size distribution, shape, surface chemistry, porosity or microcracking state, residual post-cure history and possibly a different degree of conversion from the fresh matrix. Their interfaces with the fresh liquid can evolve before exposure through wetting, uptake or swelling, and can evolve further during cure.

Maines et al. report evidence consistent with monomer ingress into recycled particles and formation of an interpenetrating network during subsequent UV exposure [1]. That mechanism is valuable because it shows that the interface need not behave as an inert crack-like boundary. It is still formulation-specific. A different cured network, monomer package or post-cure state may swell differently or form a weaker interface.

For qualification purposes, the recycled feed should therefore be assigned a controlled identity independent of the liquid resin. A statement such as 5 percent recycled material is incomplete unless the source material, curing history, particle preparation and basis of the percentage are also fixed.

4. Feedstock identity and segregation

Mechanical reuse begins before milling. The source population determines what enters the new formulation. At minimum, the record should distinguish resin product and version, lot where available, print and post-cure state, colour or filler package, contact with cleaning agents, storage history and any foreign material introduced during service or handling.

Same-colour or same-brand appearance does not establish chemical equivalence. A nominal product can change by version or lot, and printed scrap can contain support debris, contamination from another resin, pigments, fibres, inserts or surface treatments. Reincorporating such a mixed population converts an uncontrolled waste problem into an uncontrolled formulation problem.

Segregation rules should be proportional to consequence. A screening programme can deliberately study mixed streams, but the mixture itself then becomes the controlled feedstock and requires a specification. Routine production should not inherit permission from a laboratory mixture whose identity distribution is different.

5. Size reduction and particle-state definition

Cryogenic milling is used in the direct recycling literature to convert cured photopolymer and other polymer waste into powders suitable for controlled reincorporation [1,3]. ER-183 does not prescribe cryomilling as the only permitted route. Cutting, grinding or another mechanical method can be evaluated, but the resulting particle population must be measured rather than inferred from nominal mill settings.

Particle-size distribution is only one state descriptor. Shape, aspect ratio, roughness, fines fraction, agglomeration, density and surface damage can alter packing, rheology and interface area. Milling can also expose internal surfaces whose chemistry and conversion state differ from the external surface of the original printed part. A sieve cut or mean size therefore does not by itself define the recycled feed.

A practical release record should preserve both the preparation history and the measured particle state. If the milling method, screen, number of passes, temperature history or particle distribution changes materially, the previous formulation qualification should not be assumed to transfer.

6. Wetting, swelling and particle-matrix interface

The liquid matrix must wet and surround the recycled particles sufficiently for dispersion, exposure and load transfer. Where the fresh monomers penetrate or swell the cured particle, the interface can become chemically and mechanically different from a simple rigid inclusion. Maines et al. provide direct mechanistic evidence consistent with this type of interaction in their studied systems [1].

Independent DLP composite work by Wang et al. shows that particle-matrix interfacial interactions can dictate the mechanical response of highly filled photocurable composites [5]. Their particles are glass rather than recycled thermoset, so the study does not establish how a recycled-polymer interface behaves. It does establish why interfacial state cannot be omitted from interpretation of composite mechanical data.

For recycled thermoset particles, useful discriminating observations can include wetting behaviour, swelling or mass uptake under a defined liquid composition and time, microscopy of particle boundaries, fracture-surface inspection and changes caused by particle surface treatment. No single interface metric is required universally. The method should be chosen to test the failure hypothesis relevant to the formulation.

7. Dispersion, agglomeration and spatial uniformity

A nominal recycle fraction is a bulk composition value. Printing depends on the local particle population presented to each exposed layer. Agglomeration, settling, flotation, wall accumulation or incomplete mixing can make local composition differ from the batch average.

Rooney et al. report particle-size-dependent dispersion behaviour in their DLP recycled-resin composite system [2]. Gholami et al. explicitly identify uneven distribution as a concern at some particle conditions [3]. These observations support a qualification requirement for spatial and time-dependent particle state, not a universal prediction of which recycled particle will settle or agglomerate.

The sampling logic should follow the filled-resin controls of ER-036: depth, lateral position, elapsed time, temperature and shear or mixing history are part of the state record [7]. A single sample from the surface of a well-mixed bottle does not prove that the vat remains compositionally uniform during a long print.

8. Rheology and recoating

Particle addition changes flow because solid inclusions occupy volume, interact hydrodynamically and can form transient particle networks. Reynolds et al. directly measured VPP photopolymer-particle mixtures and showed that filler fraction, particle-size distribution, shear rate and temperature affect viscosity and post-shear behaviour [4]. ER-036 likewise treats rheology as a history-dependent process variable rather than a single viscosity number [7].

The recycled-particle formulation should therefore be measured under a shear and temperature history relevant to its printer and handling route. A low-shear viscosity alone cannot establish refill, recoating or recovery behaviour. Conversely, a viscosity increase does not automatically make the material unprintable if the printer architecture and process are explicitly qualified for that state.

Gholami et al. used a heated-vat strategy in their own high-particle-loading system [3]. That is evidence that process architecture can compensate for rheological burden. It is not evidence that the same temperature should be applied to another resin. Heating changes viscosity and the cure process state and therefore creates a different qualified condition.

9. Optical transport, scattering and cure

The optical effect of recycled particles can be as important as the rheological effect. A cured polymer particle can differ optically from the fresh resin, contain pigment or filler, and include voids or rough fracture surfaces; the resulting attenuation and scattering therefore require measurement rather than assumption. Gholami et al. directly observed UV-light blocking as a process limitation in particle-containing DLP systems [3].

ER-044 establishes the broader series boundary: photoabsorbing or scattering fillers can alter optical response and cure depth, and optical qualification must remain tied to wavelength, dose, thickness and formulation state [8]. ER-183 applies that requirement to recycled particles without re-owning the generic optical physics.

Qualification should compare the neat and recycled formulations using a declared optical and cure-response method. Depending on the system, this can include spectral transmission or absorbance, working-curve behaviour, conversion, cure depth, feature fidelity or another state-resolved measure. A successful print at one geometry does not prove that the same formulation has preserved the exposure margin for fine negative features, deep sections or another build position.

10. Recycled fraction is a formulation variable, not a sustainability label

Any intentional recycled-particle fraction changes the formulation composition. The denominator and basis must be explicit: mass fraction of total uncured mixture, mass relative to fresh resin, volume fraction or another declared basis. Ambiguous recycle percentages make comparison impossible.

The direct literature demonstrates that useful properties can be retained at study-specific recycled fractions [1,2], and later work explores substantially different powder-resin ratios [3]. Those numbers are experimental coordinates, not a ladder of universally permitted loadings. A higher recycled fraction can increase material reuse while simultaneously narrowing rheological or optical process margins. A lower fraction can be easier to process yet still be unacceptable for a property sensitive to defects or particle interfaces.

ER-183 therefore treats recycled fraction as a controlled independent variable. If the fraction changes outside the qualified interval, the material state changes and the relevant qualification gates reopen.

11. Printing architecture and compensating process changes

A recycled-particle formulation can sometimes be made printable by changing exposure, temperature, layer strategy, mixing or other process conditions. Such compensation is technically legitimate only if it is documented as part of the new process state.

The series framework RP-02 requires claims to remain tied to the actual material, machine, exposure, geometry, post-processing, conditioning and measurement state [6]. The implication for recycling is direct: equivalence cannot be claimed by comparing a neat resin printed under one process with a recycled formulation printed under a materially different process while ignoring the process change.

A compensating change also creates new failure hypotheses. Higher exposure can recover cure depth while increasing lateral cure or dimensional bias. Higher temperature can improve flow while changing reaction kinetics or sedimentation. A secondary thermal cure can improve conversion while changing shrinkage or thermal history. Each compensation should therefore be qualified against the response it was intended to recover and the new responses it can disturb.

12. Printability is broader than successful layer formation

A printed coupon proves that one geometry completed a process. It does not prove that the formulation has the same operating window as the neat resin. Printability qualification should include the failure modes relevant to the intended application: refill or recoating delay, trapped particles, agglomerates, local under-cure, unsupported-feature stability, dimensional fidelity, surface quality and any printer-specific separation or handling burden.

The challenge geometry should be selected from the intended use rather than from convenience. If recycled particles are expected to affect scattering, include features sensitive to optical overgrowth and under-cure. If rheology is the dominant concern, include refill distance, large cross-sections or build positions that challenge flow recovery. If particle settling is credible, compare early and late build locations or otherwise preserve the time coordinate.

The result is a process-window comparison, not a binary printed/did-not-print statement.

13. Mechanical property retention and equivalence claims

Mechanical recycling studies commonly compare a recycled formulation with a neat or virgin control [1,2]. Such comparisons are useful only when specimen state and statistical question are explicit. Retaining tensile strength does not establish retention of elongation, fracture resistance, fatigue, creep, thermal response, dimensional stability or another application-critical property.

Rooney et al. used an equivalence-test approach for a study-specific tensile comparison [2]. That is a stronger evidential form than declaring two means similar by inspection, but the equivalence margin, specimen state and property remain part of the claim. It does not establish generic material equivalence.

Particle-filled composites can fail through matrix, particle, interface or void-related mechanisms. Wang et al. show that interface state can materially control mechanical response in DLP composites [5]. Fractography or microstructural inspection is therefore useful when a property change needs mechanistic interpretation rather than merely pass/fail disposition.

14. Repeated recycling cycles

A single reincorporation cycle does not establish indefinite circularity. Each cycle can change the feed population through additional cure history, milling history, selective loss of fines or coarse particles, contamination, surface damage and accumulation of particles that have already experienced more than one matrix environment.

The current direct evidence base supports feasibility of mechanical reincorporation but is not sufficient to define a universal number of cycles. Multiple recycling cycles remain an open question across the direct evidence base. ER-183 therefore requires cycle number to be treated as a material-state variable whenever repeated recycling is claimed.

A repeated-cycle study should preserve mass balance and feed history so that performance is not maintained simply by an unreported increase in fresh-resin fraction or by selective discard of difficult recycled material. If the feed is blended across generations, the generation distribution becomes part of the specification.

15. Contamination and exclusion criteria

Mechanical grinding cannot be assumed to remove chemical or particulate contamination. A printing support contaminated with another resin, a solvent-exposed part, a service-aged component or a pigmented scrap stream can carry species that are absent from the intended fresh formulation. The correct response is not to assume that dilution makes them irrelevant.

Feed exclusion criteria should be linked to analytical capability and consequence. For a tightly controlled internal production loop, product identity and process history may be sufficient for an initial gate. For post-consumer or service-exposed parts, the unknown-contact history is a separate qualification problem and may make reincorporation unsuitable without additional sorting and analysis.

ER-183 does not provide a universal contamination threshold. It requires the recycled-feed identity to be strong enough that the resulting formulation can be described and tested.

16. Qualification architecture and decision gates

The minimum qualification architecture is a chain rather than a single recycled-content number. Each gate answers a different question and can fail independently.

Gate	Minimum evidence	Typical blocking result
Feed identity	Resin/source class, cure and service history, segregation rule	Unknown or mixed identity outside defined scope
Particle state	Size distribution plus relevant shape, fines, agglomeration and preparation history	Uncontrolled milling output or batch drift
Dispersion/rheology	State-matched mixing, sampling and flow response	Recoating/refill incompatibility or spatial segregation
Optical/cure	Wavelength- and dose-specific optical/cure comparison	Loss of through-cure, lateral fidelity or exposure margin
Interface	Evidence appropriate to wetting, swelling or load-transfer hypothesis	Weak particle-matrix boundary or uncontrolled voiding
Printing	Representative challenge geometry and build-time state	Completion only in non-representative easy coupons
Final properties	Application-relevant mechanical/thermal/functional tests	Retention of one property but failure of another critical property
Lifecycle	Storage, repeated cycles, change control and requalification triggers	Unsupported extrapolation beyond tested generation or state

No gate converts mechanical reuse into proof of environmental benefit. Any lifecycle claim remains subject to the system boundary and inventory rules of the life-cycle assessment owner.

17. Minimum reporting set

A technically useful mechanical-recycling report should permit another engineer to reconstruct the material state and the comparison. At minimum it should record:

Record block	Minimum content	Why it matters
Source waste	Product/version or defined class, lot if relevant, print/post-cure/service history	Defines what was recycled
Size reduction	Method, temperature state, mill/screen conditions and number of passes where relevant	Defines preparation history
Particle population	Size distribution, basis, morphology or agglomeration descriptors relevant to the hypothesis	Replaces nominal mill setting with measured feed state
Composition	Fresh matrix identity, recycled fraction and explicit mass/volume basis, other additives	Defines the new formulation
Mixing and hold state	Sequence, energy/time, temperature, elapsed time and sampling location	Makes dispersion state reproducible
Rheology	Method, shear history, temperature and relevant recovery/recoating metric	Connects particle state to processability
Optical/cure state	Wavelength, irradiance/dose, thickness/geometry and optical or conversion/cure metric	Detects particle-driven change in exposure response

Record block	Minimum content	Why it matters
Printing	Machine, layer/exposure strategy, build position and challenge geometry	Bounds printability claim
Post-processing	Wash, dry, post-cure and thermal history	Defines the tested final network state
Properties and statistics	Test method, conditioning, specimen population, comparator and uncertainty/equivalence rule	Bounds retained-property or equivalence claims
Recycling history	Cycle/generation number, blend rule and mass-balance treatment	Prevents hidden fresh-input or generation effects

A statement such as printed successfully with recycled resin is insufficient because neither recycled resin nor successfully identifies the material state or the property being qualified.

18. Limitations, requalification triggers and conclusions

The direct evidence base for mechanical reuse of cured VPP thermosets is still small relative to the diversity of commercial photopolymer chemistries. Maines et al. and Rooney et al. demonstrate the core route in specific systems [1,2]. Gholami et al. demonstrate a broader powder-in-photopolymer strategy, including 3D-printed thermoset waste, and directly expose the coupled rheological and optical penalties that can accompany particle addition [3]. Supporting filled-resin studies confirm that particle fraction, size distribution, shear history, temperature and interface state are plausible control variables [4,5]. These sources justify a qualification architecture, not a universal recipe.

Requalification should be triggered by changes that can alter the state chain. Examples include a new source resin or product version, changed cure or service history of the waste, changed milling method, shifted particle distribution, changed recycled fraction, new liquid matrix, altered mixing or hold time, changed printer or exposure spectrum, changed process temperature, altered post-cure or a new intended property claim. RP-02 provides the common series rule that a change in a controlled material or process element can require partial or complete requalification [6].

The engineering conclusion is narrow. Cured photopolymer thermoset waste can, in demonstrated cases, be mechanically reduced and reused as a particulate constituent in a new photocurable formulation. That material is not the original resin restored. Its recycled feed, dispersion, rheology, optical response, cure, interfaces, printability and final properties form a new controlled state. Mechanical reuse becomes technically credible when that state is measured and qualified rather than when a recycled-content percentage is merely declared.

Related Engineering Review boundaries

ER-017 owns life-cycle assessment and environmental-superiority claims.

ER-036 owns generic rheology, recoating, dispersion and state-matched sampling of highly filled VPP suspensions [7].

ER-044 owns generic photoabsorber/filler optical response and cure-depth control [8].

ER-063 and ER-074 own chemically reprocessible network mechanisms.

ER-111 to ER-113 own designed chemical cleavage, exchange and recovery routes.

ER-178 owns solvent, wash-water and contaminated-waste management.

ER-183 owns controlled mechanical size reduction and physical reincorporation of cured photopolymer waste followed by requalification of the new formulation state.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No comparative product recommendation is made. The review does not claim that a 3Dresyns material is qualified for mechanical recycling unless a separate product-specific validation states so.

Data availability and AI-assistance statement

No new experimental dataset was generated. Scientific statements derive from the cited literature and controlled Engineering Review corpus. Generative AI assisted drafting, evidence organisation and document production but is not an author. Juan Segurola retains responsibility for the final article.