

Residual-Stress Measurement in Photopolymerised Parts

Curvature, hole-drilling, diffraction, relaxation and model dependence

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Abstract

Residual stress in photopolymerised parts is not observed directly. It is inferred from deformation, strain release, diffraction, optical response or a coupled constitutive model. Each route samples a different spatial scale and stress component, and each embeds assumptions about elastic behaviour, geometry, material symmetry, time dependence and the stress-free reference state. A value obtained from a thin coating on a beam is therefore not interchangeable with a near-surface hole-drilling result or a lattice-strain measurement.

This review defines a measurement architecture for residual stress in cured photopolymers and photopolymer-based parts. Curvature and cantilever methods, incremental hole-drilling, sectioning and relaxation, diffraction and coupled in-situ instruments are compared by measurand, invasiveness and model dependence. Particular attention is given to viscoelastic recovery, cure-state evolution, fixture compliance, thickness ratios, anisotropy and the frequent absence of a usable crystalline diffraction signal in neat amorphous networks. Validation requires synthetic or reference cases, repeat measurements, independent deformation fields and sensitivity to constitutive inputs. The central conclusion is that a residual-stress result is defensible only when the released or retained strain signal and the inverse model that converts it to stress are both reported. This review does not prescribe cure-shrinkage control, warpage mechanisms or universal stress limits.

Keywords: residual stress; photopolymer; curvature; cantilever; hole-drilling; strain release; diffraction; viscoelasticity; inverse problem; uncertainty

1. Significance and scope

Residual stresses can distort a released part, reduce interfacial durability or change crack driving force. Yet the term often combines different quantities: stress during irradiation, stress remaining immediately after cure, stress after support removal and stress after conditioning. Because photopolymer networks relax, age and absorb moisture, measurement time and history are part of the measurand.

No single method gives a complete three-dimensional stress tensor at every point. Method selection begins by declaring the stress component, depth, spatial resolution and time state required.

1.1 Corpus boundary

ER-207 owns residual-stress measurement methods and their inverse models. ER-031 owns cure shrinkage, residual-stress and warpage mechanisms together with minimum process reporting. ER-195 owns stress evolution at coating-substrate interfaces as a formulation problem. ER-039 owns fatigue and time-dependent deformation in vat-printed thermosets. Cross-method dimensional metrology has no dedicated owner in the controlling registers and is not claimed here. This review does not recommend cure schedules or formulations and does not treat observed warpage as a unique stress measurement.

2. Define stress, time and reference state

For small-strain linear elasticity, total strain may be decomposed conceptually as:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^c + \boldsymbol{\varepsilon}^t + \boldsymbol{\varepsilon}^h + \boldsymbol{\varepsilon}^v$$

where the superscripts denote elastic, cure-related, thermal, hygroscopic and viscoelastic components. A stress estimate requires assumptions that separate the recoverable elastic part from the others. In a time-dependent network, the inferred stress can change during the measurement itself.

Reports should define the reference temperature and humidity, time since exposure or post-cure, support-removal time, loading history and whether stress is measured in the as-built, released or conditioned state.

3. Curvature and cantilever methods

A coating or cured layer bonded to a compliant beam produces curvature. Under the restrictive thin-film, small-deflection, isotropic and elastic assumptions associated with a Stoney-type analysis, film stress is proportional to substrate curvature:

$$\sigma \approx \frac{E_s t_s^2}{6(1-\nu_s)t_f} \Delta \kappa$$

where E_s , ν_s and t_s are substrate properties and thickness, t_f is film thickness and $\Delta \kappa$ is curvature change. This expression is not valid automatically for a thick coating, large deflection, a graded cure, viscoelastic substrate or comparable layer and substrate stiffness.

ASTM D6991 formalises a cantilever-beam route for internal stresses in organic coatings [1]. For photocuring experiments, optical delivery, fixture stiffness and beam temperature must be controlled. A measured force or deflection is the instrument response; stress

follows only through the declared beam and film model.

4. Instrument compliance and in-situ evolution

An in-situ cantilever or photo-rheometer can track stress development during exposure, but the specimen and instrument form a coupled mechanical system. Stiff fixtures constrain shrinkage and can generate a different stress path from a freely deforming part. Compliant fixtures permit movement but may reduce signal.

Luo, Hiejima and Taki combined real-time FTIR and a photo-rheometer with a chemo-mechanical model for UV-curable resin [3]. Their model reproduced selected quasi-equilibrium conditions but showed limitations in early non-equilibrium and post-vitrification regimes. Xue and co-workers likewise reported that instrument stiffness and specimen thickness affect cantilever-based curing-stress evolution [4]. These studies support measurement-model caution; their numerical results are not universal material properties.

Earlier cantilever-instrument analysis also treated fixture and specimen mechanics as part of the measurement system rather than as negligible hardware [6].

5. Hole-drilling and local strain release

Hole-drilling estimates near-surface in-plane residual stresses from strains released around a small blind hole. A strain-gauge rosette or full-field optical method measures the relaxation field. ASTM E837 limits the classical method to isotropic, linearly elastic behaviour and highlights its decreasing sensitivity with depth [2]. The method is semi-destructive and can be affected by local yielding.

For photopolymers, drilling heat, cracking, tool forces and viscoelastic relaxation can contaminate the release signal. Mechanical properties used in the calibration coefficients should represent the measurement state and direction. Incremental depth steps can estimate a non-uniform profile, but each increment changes geometry and accumulates alignment and timing uncertainty.

6. Sectioning, slitting and layer removal

Cutting a specimen, releasing a support or removing a layer changes the traction boundary and produces deformation. Digital image correlation, profilometry or displacement gauges can map this relaxation. Stress is then reconstructed through an elastic or viscoelastic model.

Layer-by-layer photopolymerisation has been addressed directly in published residual-stress work [5], establishing relevance without making any one release geometry universally valid.

The method is attractive for complex printed parts because the release can be placed near a suspected region. It is also sensitive to cut width, cutting sequence, fixture motion, heat and material removed. Deformation measured long after the cut combines instantaneous elastic release with creep, moisture change and possible damage. Timing should therefore be recorded from the release event.

7. Diffraction methods and their conditional applicability

X-ray and neutron diffraction infer elastic lattice strain from changes in crystallographic spacing. In a suitable crystalline phase,

$$\epsilon_{hkl} = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}}$$

and stress is inferred using diffraction elastic constants and a stress model. The stress-free spacing d_0 is a critical reference and may depend on composition, cure and temperature.

Many neat crosslinked photopolymers are predominantly amorphous and do not provide narrow, stable lattice reflections suitable for conventional diffraction stress analysis. Diffraction can become relevant when a crystalline polymer fraction, filler or reinforcement provides interpretable peaks, but the measured phase stress need not equal the macroscopic matrix stress. Phase load sharing, texture, peak overlap and radiation penetration must be evaluated. Absence of a diffraction result is not evidence of zero residual stress.

8. Optical methods and birefringence

Photoelasticity and birefringence can map optical retardation associated with stress-induced anisotropy in transparent materials. A simplified stress-optic relation is:

$$\Delta n = C(\sigma_1 - \sigma_2)$$

where C is a stress-optic coefficient. Cure-induced molecular orientation, refractive-index gradients, thickness variation and frozen anisotropy can also contribute. Quantitative use requires wavelength, thickness, coefficient calibration and a suitable optical model. The method typically reports an integrated principal-stress difference rather than the full tensor.

Raman peak shifts or fluorescence probes can be stress sensitive after calibration, but chemical conversion, temperature and environment may shift the same spectral features. Such measurements remain model-based and material specific.

9. Inverse reconstruction and identifiability

Let measured data y depend on a stress field σ through a forward operator F :

$$y = F(\sigma, \theta) + \eta$$

where θ contains geometry and constitutive parameters and η represents measurement error. Recovering σ may be non-unique, especially when surface deformation is used to infer an internal field. Regularisation stabilises the solution but introduces prior assumptions.

The report should state mesh, boundary conditions, constitutive law, fixed and fitted parameters, regularisation and sensitivity. A close fit to the measured displacement is necessary but not proof that the reconstructed stress field is unique.

10. Viscoelasticity and measurement time

Photopolymer networks may relax over seconds to months. If the relaxation modulus is $G(t)$, a linear-viscoelastic stress history can be expressed schematically as:

$$\sigma(t) = \int_0^t G(t-\tau) \, d\epsilon(\tau)$$

where ϵ represents the mechanically constrained strain history. A curvature or release experiment that takes appreciable time relative to relaxation cannot be analysed as instantaneous elasticity without validation.

Report the acquisition window and fit both immediate and delayed deformation when relevant. Temperature control matters because a small thermal change can alter both dimensions and relaxation rate.

11. Calibration, validation and uncertainty

A defensible hierarchy includes:

- 1 calibration of displacement, strain or curvature channels;
- 2 fixture-compliance and thermal-drift controls;
- 3 a known mechanical loading case for the forward model;
- 4 repeat specimens and repeated analysis;
- 5 sensitivity to elastic or viscoelastic properties and reference state;
- 6 comparison between at least two independent observables where feasible; and
- 7 validation on a geometry or exposure condition not used for fitting.

Uncertainty includes measurement noise, spatial resolution, zero reference, thickness, elastic constants, anisotropy, fixture stiffness, cutting or drilling geometry, timing and inverse-model choices. A single standard deviation from repeated scans does not include model-form uncertainty.

12. Interpretation matrix

Observation	Supported interpretation	Unsupported leap
A bonded beam changes curvature during cure	The constrained specimen-fixture system developed a bending response	A universal bulk residual stress is known
A drilled region releases strain	Near-surface stress contributed under the method assumptions	The complete through-thickness tensor is measured
A cut part deforms reproducibly	Stored strain is released under the declared cut and timing	Cure shrinkage is the only cause
A crystalline filler peak shifts	The diffracting phase has a calibrated lattice-strain response	Neat amorphous matrix stress is equal to that phase stress
An inverse model fits the displacement field	The model reproduces the selected observable	The recovered internal stress field is unique

13. Minimum reporting set

Report formulation class and reinforcement; print orientation and geometry; cure and post-cure history; supports and release sequence; conditioning and measurement time; stress component and reference state; measurement principle, hardware, calibration and spatial resolution; specimen and fixture dimensions; raw force, displacement, strain, curvature, diffraction or optical data; constitutive properties and how they were measured; equations, boundary conditions and inverse settings; damage or relaxation controls; repeats; sensitivity and uncertainty; and whether each reported quantity is observed, derived or model-inferred.

14. Knowledge boundary

Full-field residual stress in an amorphous, viscoelastic and spatially heterogeneous printed photopolymer remains difficult to identify uniquely. Surface-release methods lose sensitivity to deep self-equilibrating stresses. Diffraction may have no suitable lattice marker. Stress-optic calibration can evolve with cure. Agreement between two methods can still reflect shared constitutive assumptions.

15. Limitations

This review does not explain cure-shrinkage or warpage mechanisms, prescribe formulation changes, define safe or acceptable stress limits or qualify fatigue life. It does not transfer calibration coefficients between resins. Standards written for coatings or linearly elastic materials require an explicit applicability assessment before use with a printed photopolymer.

16. Conclusions

Residual stress is inferred from a response and a model. Curvature methods are efficient for constrained layers, hole-drilling and cutting reveal stress through local release, diffraction is conditional on a suitable crystalline marker, and optical methods require calibrated stress sensitivity. Time dependence, fixture compliance and the stress-free reference state can dominate the result. Reporting both the measured signal and the inverse assumptions is therefore the minimum basis for a defensible residual-stress value.

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