

Cure-Shrinkage Stress at the Coating-Substrate Interface

Substrate Modulus, Thermal Mismatch and Adhesion Failure in Radiation-Curable Coatings

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Statement of Significance

A radiation-curable coating is restrained as soon as its developing network can transmit force to a substrate. Conversion then creates a coupled problem: chemical shrinkage, modulus growth, stress relaxation, substrate compliance and temperature history compete to determine whether the result remains flat and adherent or develops curl, cracking or delamination. ER-195 defines this interface-centred problem without reducing it to a single shrinkage number. It also separates cure-generated stress from later thermal mismatch and from unrelated causes of adhesion loss.

Abstract

Radiation-curable coatings develop internal stress when polymerisation shrinkage is constrained after gelation. The observable consequence depends not only on free shrinkage, but also on the evolving coating modulus, relaxation before vitrification, coating thickness, substrate stiffness, laminate symmetry, cure rate and thermal history. Direct studies show that formulation and irradiation intensity alter gelation, vitrification and stress development in UV-curable acrylates; that coupled kinetic-mechanical models can reproduce some stress regimes while failing in early non-equilibrium or post-vitrification regimes; and that substrate compliance and annealing can strongly change curl in a UV-coated semi-rigid laminate [1-4]. A two-step photocuring study further demonstrates that constraint stiffness is an experimental coordinate, not a background constant [5]. ER-195 converts this evidence into a bounded qualification framework for coatings on inert substrates. No universal stress, modulus, thickness, coefficient-of-thermal-expansion, adhesion or cure-schedule limit is proposed. Curl is treated as a system response, not a direct stress measurement, and adhesion failure is treated as a competing-mechanism diagnosis.

Keywords: radiation-curable coating; cure shrinkage; residual stress; coating-substrate interface; substrate modulus; thermal mismatch; curl; adhesion failure

1. Scope and ownership

ER-195 addresses the mechanical consequence of curing a radiation-curable coating while it is bonded to an inert substrate. “Inert” means that the substrate is not itself undergoing the coupled photochemical evolution addressed by ER-168, which owns coating and encapsulation of reactive photopolymer substrates, including surface cure state, residual-species migration, adhesion and barrier qualification. It does not mean that the surface is chemically irrelevant, perfectly rigid or immune to temperature and moisture.

Within the named sub-series *Radiation Curing Beyond Additive Manufacturing*, ER-195 examines the same photochemistry, oxygen-inhibition, attenuation, interfacial and qualification principles in coatings rather than only in printed layers. It does not extend its evidence or claims to films, inks or bulk-applied materials outside the coating-substrate systems addressed here.

The review owns the force balance among coating shrinkage, evolving modulus, relaxation, thickness, substrate compliance and thermal history, and its expression as curvature, cracking or loss of adhesion. ER-031 retains residual stress in printed parts; ER-096 retains general thermal-expansion mismatch; ER-168

retains coating and encapsulation of reactive photopolymer substrates; ER-171 retains design-values methodology for printed photopolymers; ER-097 retains wetting.

The five-source evidence core includes two full directly read primary works and three primary records read at complete-abstract depth [1-5]. The formulations, instruments, irradiation conditions and geometries remain specific to their studies.

2. Shrinkage becomes stress only under constraint

Polymerisation reduces the free volume of many reactive formulations. Before a mechanically connected network forms, part of that contraction can be accommodated by flow. After gelation, additional contraction is increasingly resisted by the substrate and by already formed network regions. The resulting stress therefore depends on when shrinkage occurs relative to gelation, vitrification and relaxation.

A useful conceptual statement is

$$\sigma_c(t) \sim E_c(t)[\varepsilon_{sh}(t) - \varepsilon_{rel}(t) - \varepsilon_{sub}(t)],$$

where $E_c(t)$ is the evolving coating modulus, ε_{sh} is the contraction that would occur without constraint, ε_{rel} is deformation relieved by viscous or viscoelastic response, and ε_{sub} represents strain accommodated by the substrate-assembly system. This is an organising scaling statement at a single instant, not a validated constitutive equation. Because the modulus grows during cure, early and late shrinkage contribute unequally; quantitative use requires an incremental or hereditary formulation that weights each constrained-strain increment by the modulus and relaxation state prevailing at that time.

Schmidt et al. showed in selected highly functional acrylates that composition and UV intensity shifted gelation, vitrification, final conversion and internal-stress development [3]. Li et al. similarly followed stress and volume change through gelation, vitrification and reaction saturation [4]. These studies support treating stress as a cure-history variable rather than a fixed material constant.

3. Conversion alone does not predict final stress

Conversion is necessary to describe reaction progress, but equal conversion need not imply equal stress. The network may have formed at different rates, temperatures or mobility states. Stress can relax while the material remains mobile and accumulate rapidly once mobility becomes restricted.

Luo et al. measured conversion and polymerisation-induced normal force simultaneously in a defined DUDM/BAPO system and developed a coupled kinetic-shrinkage-stress model [2]. Their model performed well in specified quasi-equilibrium conditions but required empirical correction and showed larger deviations in early non-equilibrium or post-vitrification elastic-dominated regimes [2]. The limitation is as important as the agreement: model validity has a domain.

A coating qualification should therefore report conversion together with the time-resolved mechanical response or a defensible proxy. A high final conversion does not prove low residual stress, and a low measured force in one fixture does not prove adequate adhesion in a coated article.

4. Cure rate changes the stress pathway

Irradiance, spectrum, exposure time, atmosphere and formulation affect the reaction rate and therefore the sequence of gelation, heat release, vitrification and relaxation. Schmidt et al. found intensity-dependent effects on conversion at vitrification and on final stress in their acrylate systems [3]. Luo et al. found that a model calibrated to specified irradiation histories did not generalise equally across all dynamic regimes [2].

The engineering implication is not that slow cure is always safer. A slower early stage can preserve relaxation time, but it can also leave an under-reacted or oxygen-affected surface, lengthen production exposure or alter

the final network. A faster stage can raise conversion efficiently but can move shrinkage into a high-modulus state. Cure schedule must be optimised against the complete claim set, not residual stress alone.

5. Substrate modulus controls the visible response

The same coating force produces different deformation on rigid, semi-rigid and compliant substrates. A rigid substrate can remain apparently flat while storing a high interfacial driving force. A compliant substrate may curve and thereby reveal or partially accommodate the imbalance. Curvature is therefore a response of the whole coating-substrate construction.

Burcham et al. studied a semi-rigid filled-PVC laminate with UV-curable topcoat and backcoat layers [1]. They varied coating weight and cure conditions and showed that the central substrate resisted coating-driven bending at room temperature but softened during annealing, allowing substantially more curvature in the studied construction [1]. Bao et al. independently treated constraint stiffness as a controlled experimental variable in a photocuring shrinkage-stress study [5].

These sources support explicit control of substrate modulus at cure, test and service temperatures. They do not supply a universal stiffness boundary between rigid and flexible substrates.

6. Thickness and laminate asymmetry govern curvature

Coating thickness changes both the total shrinking material and the bending moment relative to the neutral axis. In a multilayer article, stress balance depends on the location, thickness and modulus of every mechanically active layer.

In the Burcham laminate, coating weight was a dominant variable for curl, while cure conditions and subsequent annealing also affected the result [1]. At higher coating weights, cracking during annealing limited the observable curvature in some specimens [1]. This distinction matters: reduced measured curl after cracking is not evidence of reduced stored driving force. It may mean that the system released force by damage.

Qualification should therefore document wet and dry coating thickness, through-thickness cure state, substrate thickness, layer order, coating on one or both faces and the time and temperature at which flatness is measured.

7. Thermal history can expose or add mismatch stress

The temperature history has at least three roles. First, temperature during cure affects kinetics and mobility. Second, post-cure heating can promote relaxation, further reaction or substrate softening. Third, cooling or service cycling generates differential strain when coating and substrate have different effective thermal expansion.

Burcham et al. directly observed large changes in curl after thermal annealing and attributed the dominant effect in their construction to softening of the semi-rigid substrate, with limited additional dark cure depending on formulation [1]. This supports a strict distinction between cure-generated stress and the mechanical expression of that stress after the substrate changes state.

ER-195 treats coefficient-of-thermal-expansion mismatch as a required qualification variable, but the controlled evidence does not justify a universal mismatch limit. The residual strain after cure and the thermal strain imposed during service must be evaluated for the actual coating, substrate, thicknesses, temperature range and time scale.

8. Curl is not a direct stress measurement

Curvature can be a sensitive production indicator, but converting it into coating stress requires a model with appropriate assumptions about geometry, layer properties, thickness, adhesion and linearity. A flat specimen

can retain interfacial stress if the substrate is stiff or if opposing layers balance. A curved specimen can later flatten through relaxation without recovering its original network state.

The most defensible use of curl is comparative within a locked construction and measurement protocol. If a stress value is calculated, the report should state the mechanical model, the measured substrate and coating properties, the temperature and conditioning state, and whether cracking or slip invalidated the assumptions.

9. Adhesion loss has competing causes

Shrinkage stress can reduce the margin against interfacial separation, but adhesion failure can also originate from inadequate wetting, contamination, weak boundary layers, chemical incompatibility, moisture, cure gradients, defects or environmental degradation. ER-195 does not assign every delamination to shrinkage.

Li et al. identify interfacial strength and dimensional stability as consequences threatened by photocure-generated internal stress [4]. Burcham et al. directly connect a laminate force imbalance with curl and, under some annealing conditions, coating cracking [1]. These observations justify including adhesion and fracture response in qualification, but do not create a universal causal diagnosis.

A useful failure analysis should compare interfacial and cohesive fracture location, cure state near the interface, surface preparation, thickness, residual curvature, temperature history and damage chronology. A lower pull-off value after a process change is not sufficient to identify shrinkage stress as the cause.

10. Porous, compliant and rigid substrates require different controls

A porous substrate can absorb formulation and create a mechanical interphase. A compliant polymer can relax or soften with temperature. A rigid metal or glass substrate can suppress visible curvature while retaining stress. These are different boundary conditions even when the same coating formulation and nominal exposure are used.

ER-195 therefore does not organise qualification by substrate marketing category. It organises it by measured mechanical and transport behaviour: modulus versus temperature and time, thickness, porosity or uptake, surface state, thermal expansion, moisture response and constraint geometry.

The transfer from one substrate to another requires a bridge covering the affected variables. Similar surface energy or initial adhesion does not prove similar cure-stress response.

11. Stress mitigation is a multi-objective optimisation

Potential controls include formulation changes, reduced functional density, flexible or hyperbranched components, fillers, staged exposure, delayed high-intensity exposure, lower coating thickness, balanced coatings, altered cure temperature and substrate support. Each control can change other properties.

Schmidt et al. showed that hyperbranched components shifted vitrification and reduced internal stress in their selected blends [3]. Bao et al. reported stress reduction using a quantified two-step protocol across their tested conditions, including different constraint stiffness and filler content [5]. These are direct demonstrations, not universal recipes.

A mitigation is acceptable only if it preserves the required conversion, surface cure, chemical resistance, hardness, adhesion, appearance, dimensional stability and service durability. The evidence must be generated for the final formulation and construction.

12. Verification framework

A bounded verification programme should separate four layers:

1. **Reaction state:** conversion and cure gradient at defined times and locations.
2. **Coating mechanics:** modulus, relaxation and shrinkage or force evolution under declared conditions.
3. **Construction response:** curvature, warpage, cracking and layer interaction.

4. Interface performance: adhesion or fracture response before and after relevant thermal, humidity and ageing exposures.

Luo et al. demonstrate simultaneous reaction and force measurement and disclose where their predictive model loses accuracy [2]. Burcham et al. combine cure-state methods with laminate-level curl and damage observations [1]. Together they support measurement at more than one layer of the problem.

Acceptance criteria remain claim-specific. ER-195 supplies no universal maximum stress, curvature or adhesion loss.

13. Change control

Potential requalification triggers include monomer or oligomer composition, functionality, photoinitiator, pigment or filler, coating thickness, cure atmosphere, source spectrum, irradiance, exposure sequence, line speed, substrate identity, substrate thickness, porosity, modulus, surface preparation, coating on the opposite face, cure temperature, annealing and service temperature range.

A bridging argument is acceptable when retained tests are demonstrably sensitive to the affected reaction, mechanical and interfacial mechanisms. A nominally unchanged final conversion is not a sufficient bridge if the cure rate, gelation history, substrate compliance or temperature profile changed.

14. Minimum reporting

A reusable record should identify formulation and lot, substrate and surface preparation, substrate thickness and mechanical state, wet and dry coating thickness, source and spectral range, irradiance-measurement plane, exposure sequence, atmosphere, cure and specimen temperatures, time to each measurement, conversion method, force or stress method, curvature method, adhesion or fracture method, conditioning and observed failure mode.

Calculated stress should be separated from directly measured force and from curvature. The constitutive model and assumptions should be stated. Reports should disclose cracked, slipped or partially delaminated specimens because those events can invalidate stress calculations or make reduced curvature misleading.

15. Evidence limitations

The evidence core is sufficient for a bounded critical review, not a systematic review of all radiation-curable coatings or substrates. Two full sources use specific methacrylate or acrylate systems and constrained geometries [1,2]. Three sources are used at complete-abstract depth [3-5].

The evidence does not establish universal modulus, thickness, irradiance, dose, conversion, stress, curvature, thermal-expansion or adhesion limits. Direct quantitative thermal-mismatch transfer across metal, glass, wood, polymer and porous substrates remains outside the evidence. Electron-beam-specific stress development is not separately qualified.

16. Conclusions

Cure-shrinkage stress at a coating-substrate interface is a coupled history, not a single formulation number. Stress begins to matter when shrinkage occurs in a network capable of transmitting force, then evolves with conversion, modulus growth, relaxation, vitrification and temperature.

Direct evidence shows that formulation and irradiation history alter internal-stress development [2-4], that constraint stiffness is an experimental control [5], and that substrate compliance, coating weight and annealing can transform a UV-coating force imbalance into curl or cracking [1]. The absence of visible curvature does not prove the absence of stress, and reduced curvature after damage does not prove improvement.

The defensible qualification rule is to measure reaction state, coating mechanics, construction response and interface performance separately, then reconnect them for the actual substrate and thermal history. Adhesion failure must be diagnosed against competing mechanisms. No universal stress or mismatch threshold replaces that evidence.

Related Engineering Review boundaries

ER-031 owns cure shrinkage and residual stress in printed parts. ER-096 owns thermal expansion and mismatch generally. ER-168 owns coating and encapsulation of reactive photopolymer substrates, including surface cure state, residual-species migration, adhesion and barrier qualification. ER-171 owns design-values methodology for printed photopolymers. ER-097 owns wettability. ER-195 owns cure-generated interfacial stress and its mechanical consequences for radiation-curable coatings on inert substrates.

References

- [1] Burcham, L. J.; Fields, S.; Allenbach, R.; Hoyle, C. E.; Wei, H. Curing Mechanisms Affecting Curl in UV-Coated Laminate Constructions of Semi-Rigid Materials. *RadTech e|5 UV & EB Technology Expo & Conference Proceedings* (2006), paper 047.
- [2] Luo, G.; Hiejima, Y.; Taki, K. Measurement and prediction of polymerization residual stress evolution under UV intensity from 10 to 30 mW/cm². *Journal of Photopolymer Science and Technology* 38(5) (2025) 389-397. <https://doi.org/10.2494/photopolymer.38.389>
- [3] Schmidt, L. E.; Schmäh, D.; Leterrier, Y.; Månson, J.-A. E. Time-intensity transformation and internal stress in UV-curable hyperbranched acrylates. *Rheologica Acta* 46 (2007) 693-701. <https://doi.org/10.1007/s00397-006-0163-6>
- [4] Li, L.; Wu, W.; Chen, Q.; Liu, R. Deciphering Internal Stress Dynamics: Generation and Relaxation Mechanisms in Photocuring. *Macromolecules* 59(5) (2026) 2715-2723. <https://doi.org/10.1021/acs.macromol.5c02315>
- [5] Bao, L.; Wang, K.; Wang, Z. Quantifying the Optimal Two-Step Photocuring Protocol for Maximally Reduced Shrinkage Stress during Photopolymerization. *Experimental Mechanics* 65 (2025) 1031-1042. <https://doi.org/10.1007/s11340-025-01193-y>

Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. This review does not claim that any 3Dresyns coating, resin or process is qualified for a particular substrate, structure or regulated use.

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Data availability statement

No new experimental dataset was generated. This review is based exclusively on the scientific literature cited in the References section.