

Cure Shrinkage Coupled to Resin Flow: Free Surfaces, Cavitation, Feeding and Internal Defect Formation

Treating polymerisation contraction as a coupled solidification-and-feeding problem rather than a single shrinkage percentage

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ER-354 · Engineering Review · Version 0.2 · 1 October 2026

Abstract

This review examines when cure shrinkage can no longer be treated as a purely local strain because liquid feeding, free-surface motion and pressure evolution become part of the defect mechanism. Gelation shifts the material from flow accommodation toward solid stress accumulation, while viscosity growth increases the pressure required to replenish shrinking regions. The measurement architecture combines dilatometry or density-based shrinkage mapping, free-surface DIC, micro-CT of internal voids and pressure sensing in confined resin channels. Comparing open, sealed and vented geometries separates feeding limitation from intrinsic shrinkage. The resulting qualification framework identifies when a geometry requires a feeding path or vent and when cavitation or internal void formation must be included explicitly.

Keywords: cure shrinkage; resin flow; cavitation; free surface; feeding; internal voids

1. Qualification problem: shrinkage-fed resin flow

A useful qualification record for shrinkage-fed resin flow must state which engineering decision the evidence supports. Here that record addresses when a geometry needs a feeding path or vent, then whether dimensional compensation can be geometric or must be process-based, and finally whether void risk is dominated by trapped gas, cavitation or insufficient resin mobility; the corresponding regime axes are Deborah number, capillary number, and cavitation criterion. [2]

1.1 Scope boundary.

ER-354 owns cure shrinkage coupled to resin feeding and free-surface flow. ER-351 owns thermal accumulation, ER-353 natural convection, ER-359 gravity/drainage, and ER-34 separation mechanics; they enter only where they change pressure, replenishment or defect formation during shrinkage.

2. Governing balances for shrinkage-fed resin flow

Shrinkage-fed flow is reduced to the relations below so that gelation, viscous feeding, capillarity, and cavitation are not conflated.

volumetric chemical shrinkage can be represented by an eigenstrain proportional to conversion increment

mass conservation requires liquid feeding before gelation if a shrinking zone remains connected to mobile resin

after gelation, the same volume deficit is redirected toward stress, free-surface motion or void growth

Together they identify whether a defect is limited by feeding kinetics, interfacial forces, or loss of tensile pressure margin.

3. Regime boundaries for shrinkage-fed resin flow

The regime indicators below are used to choose between feeding-path design, geometric compensation, and process-based void control.

Table 1. Regime indicators for shrinkage-flow coupling.

Indicator	Engineering meaning	Use
Deborah number	cure or gel time relative to viscous relaxation	The evidence behind 'when a geometry needs a feeding path or vent' remains portable only while Deborah number stays inside the demonstrated band for cure or gel time relative to viscous relaxation.
capillary number	viscous pressure loss relative to interfacial tension	The evidence behind 'whether dimensional compensation can be geometric or must be process-based' remains portable only while capillary number stays inside the demonstrated band for viscous pressure loss relative to interfacial tension.
cavitation criterion	tensile hydrostatic stress relative to nucleation resistance	The evidence behind 'whether void risk is dominated by trapped gas, cavitation or insufficient resin mobility' remains portable only while cavitation criterion stays inside the demonstrated band for tensile hydrostatic stress relative to nucleation resistance.

Any untested combination of gelation, capillary loading, or cavitation margin is treated as a new shrinkage-flow state.

4. Couplings that move the shrinkage-fed resin flow

Gelation moves the system from flow accommodation toward solid stress accumulation.

Viscosity growth increases feeding pressure drop while shrinkage continues.

Trapped gas, free surfaces and compliant boundaries change the available accommodation mechanism.

5. Failure signatures and false diagnoses

For qualification, microvoids or cavitation pockets in poorly fed regions, surface sink or meniscus motion and dimensional undershoot despite nominal optical cure depth are treated as independent rejection modes. Their diagnostic evidence is drawn from dilatometry or density-based conversion-shrinkage mapping, digital image correlation on free surfaces or compliant molds and micro-CT for internal void topology, with each measurement interpreted against the branch it can actually discriminate.

Table 2. Failure-mode discrimination for shrinkage-flow coupling.

Failure mode	Observable signature	Discriminating evidence
microvoids or cavitation pockets in poorly fed regions	dilatometry or density-based conversion-shrinkage mapping	compare open-surface, sealed and vented geometries
surface sink or meniscus motion	digital image correlation on free surfaces or compliant molds	vary flow-path length at matched conversion
dimensional undershoot despite nominal optical cure depth	micro-CT for internal void topology	change gel point through chemistry or temperature while holding final conversion comparable
residual stress and delamination when shrinkage is constrained	pressure sensing in confined resin channels during cure	seed controlled nuclei to distinguish cavitation from trapped-air expansion

Table 2 is therefore a discrimination matrix rather than a checklist: the direction of change across rows determines which failure explanation survives.

6. Measuring shrinkage-fed resin flow with traceable uncertainty

Measurement traceability is established row by row in Table 2, including calibration, repeatability and the state conditions under which each channel was acquired. An uncertainty-controlled perturbation of tensile pressure margin is the first stress test for shrinkage-fed resin flow; only after that result is bounded is independent resolution of chemical shrinkage and liquid feeding before gelation interpreted; during metrology of shrinkage-fed resin flow, tensile pressure margin is resolved against void growth. The record keeps separate monitoring of void growth outside that inference and reports it as an independent line of evidence; the uncertainty record for shrinkage-fed resin flow keeps void growth separate from chemical shrinkage.

7. Experiments that discriminate competing mechanisms

Causal discrimination uses all four Table 2 interventions, but each is analysed against its own predicted signature before cross-comparison. Qualification of shrinkage-fed resin flow treats a causal contrast between chemical shrinkage and tensile pressure margin as one axis and a replicate test of void growth as another; during the causal challenge for shrinkage-fed resin flow, void growth is tested against chemical shrinkage. Between them, a boundary challenge involving liquid feeding before gelation supplies the deliberate challenge that determines whether the apparent transfer is mechanistic or merely coincidental; the experiment for shrinkage-fed resin flow separates chemical shrinkage from liquid feeding before gelation.

8. Model identification and validation for shrinkage-fed resin flow

Rows three and two provide independent identifiability and transfer tests, respectively. [2] [3,4] [5,6] The uncertainty budget is mapped directly onto the three acceptance limits in Table 3 and is not hidden inside a single safety factor. The shrinkage-fed resin flow workflow deliberately separates prediction against tensile pressure margin from parameter estimation for chemical shrinkage and liquid feeding before gelation; this avoids fitting the challenge into the quantity being qualified; within model identification for shrinkage-fed resin flow, chemical shrinkage is not fitted through liquid feeding before gelation. An uncertainty-bounded check on void growth is then examined on its own terms before any transfer statement is retained; prediction for shrinkage-fed resin flow keeps liquid feeding before gelation independent of tensile pressure margin. [1]

9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for shrinkage-flow coupling.

Decision	Minimum evidence	Acceptance logic
when a geometry needs a feeding path or vent	Support when a geometry needs a feeding path or vent with a traceable dilatometry or density-based conversion-shrinkage mapping series spanning the claimed range and an independent repeat at the boundary state.	Acceptance requires agreement of repeated dilatometry or density-based conversion-shrinkage mapping measurements after 'compare open-surface, sealed and vented geometries' and no onset of microvoids or cavitation pockets in poorly fed regions across the qualified states.
whether dimensional compensation can be geometric or must be process-based	The minimum record for whether dimensional compensation can be geometric or must be process-based is digital image correlation on free surfaces or compliant molds measured across the relevant state interval with calibration, repeatability and decision uncertainty reported.	Pass the row only when the measured response to 'vary flow-path length at matched conversion' remains within uncertainty and the diagnostic pattern for surface sink or meniscus motion is not observed.
whether void risk is dominated by trapped gas, cavitation or insufficient resin mobility	Establish whether void risk is dominated by trapped gas, cavitation or insufficient resin mobility from repeated micro-CT for internal void topology measurements on both sides of the intended transfer boundary.	The candidate is acceptable when 'change gel point through chemistry or temperature while holding final conversion comparable' yields a repeatable micro-CT for internal void topology trend consistent with the qualified envelope and does not reveal dimensional undershoot despite nominal optical cure depth.

For shrinkage-fed resin flow, the evidence chain starts with tested ranges in chemical shrinkage and liquid feeding before gelation; inside the shrinkage-fed resin flow envelope, liquid feeding before gelation and tensile pressure margin define different transfer limits. It then adds a separate boundary for tensile pressure margin, while an explicit transfer limit on void growth is retained as a separate control so the three sources of information cannot compensate silently; qualification of shrinkage-fed resin flow bounds tensile pressure margin separately from void growth.

10. Design consequences for shrinkage-fed resin flow

The practical design route begins with an implementation check on tensile pressure margin; while when a geometry needs a feeding path or vent is controlled independently, a design change governed by chemical shrinkage is changed only within the validated response range; during design implementation for shrinkage-fed resin flow, tensile pressure margin is constrained by void growth. Any design outside those conditions returns to measurement rather than being accepted by similarity of settings; the shrinkage-fed resin flow design record separates void growth from chemical shrinkage.

11. Evidence gaps for shrinkage-fed resin flow

Three independent checks structure the shrinkage-fed resin flow assessment; for unresolved shrinkage-fed resin flow transfer, void growth is studied separately from chemical shrinkage. Scale transfer of chemical shrinkage establishes the primary state, independent replication of void growth tests whether that state survives transfer, and uncertainty in liquid feeding before gelation versus tensile pressure margin is the perturbation used when the two disagree; the evidence gap in shrinkage-fed resin flow distinguishes chemical shrinkage from liquid feeding before gelation.

12. Qualification outcome for shrinkage-fed resin flow

The qualification outcome is a bounded state space, not a universal material property; each Table 3 row must remain within its validated range. For the shrinkage-fed resin flow problem, a renewed-evidence trigger when void growth changes defines the independent cross-check rather than a tuning variable; at final qualification of shrinkage-fed resin flow, chemical shrinkage is reconciled with liquid feeding before gelation. The main inference uses agreement between measurement and prediction for chemical shrinkage, whereas causal evidence that separates liquid feeding before gelation from tensile pressure margin is reserved for the boundary test that can overturn the proposed interpretation; the closing shrinkage-fed resin flow claim keeps liquid feeding before gelation distinct from tensile pressure margin.

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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.

Data availability

No new experimental dataset was generated for this review.