

Shear-Induced Alignment Before Photocure: Fibres, Platelets and Orientation Retention Beyond Liquid-Crystal Elastomers

Using controlled flow history to orient anisotropic fillers while keeping liquid-crystal-elastomer director programming outside scope

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Abstract

Shear-induced orientation should be qualified through the competition between hydrodynamic rotation, particle interactions, confinement and cure arrest rather than through a single mean angle. Shear history can align fibres or platelets while simultaneously changing dispersion and viscosity, and confinement can bias the accessible orientation distribution near walls. The proposed evidence combines controlled-history rheometry with flow birefringence or polarised imaging, three-dimensional orientation tensors from microscopy or CT, and mechanical testing along and across the programmed direction. A step-shear experiment followed by a variable dark delay directly measures orientation retention before gelation. This framework supports decisions on the shear rate, residence time and cure timing required to achieve a target anisotropy with known relaxation margin.

Keywords: shear alignment; fibres; platelets; orientation tensor; photocure; anisotropic composite

1. Qualification problem: shear alignment

This review treats shear alignment as a bounded engineering state rather than a descriptive effect. It asks required shear rate and residence time for target anisotropy, establishes maximum exposure delay before orientation loss, and resolves whether confinement-induced gradients are acceptable for the application, with rotational Peclet number, Deborah number, and aspect ratio retained to prevent false transfer between regimes. [4]

1.1 Scope boundary.

ER-358 owns shear-induced orientation before or during photocure outside the dedicated liquid-crystal-elastomer scope. ER-356 and ER-357 own electric and magnetic alignment, ER-359 gravity-driven segregation, and ER-360 model validation; they are referenced only to distinguish torque, transport and arrest mechanisms.

2. Governing balances for shear alignment

Shear alignment is governed by the relations below, which distinguish rotational transport, structural relaxation, and particle geometry.

Jeffery-type rotation describes isolated ellipsoids in simple shear in the dilute limit

orientation evolution in concentrated suspensions additionally depends on collisions, excluded volume and rheology

post-shear relaxation competes with cure-induced viscosity rise and gelation

They are retained independently because high alignment can still relax before cure or vary strongly with confinement.

3. Regime boundaries for shear alignment

The shear-alignment map indicates when anisotropy, exposure delay, or confinement gradients require a separate qualification case.

Table 1. Regime indicators for shear-induced orientation.

Indicator	Engineering meaning	Use
rotational Peclet number	shear-driven alignment relative to Brownian rotation	For 'required shear rate and residence time for target anisotropy', report rotational Peclet number for both the qualified and candidate conditions; movement in this quantity reflects a change in shear-driven alignment relative to Brownian rotation.
Deborah number	structural relaxation time relative to process time	For 'maximum exposure delay before orientation loss', report Deborah number for both the qualified and candidate conditions; movement in this quantity reflects a change in structural relaxation time relative to process time.
aspect ratio	particle geometry controlling Jeffery orbit and alignment sensitivity	For 'whether confinement-induced gradients are acceptable for the application', report aspect ratio for both the qualified and candidate conditions; movement in this quantity reflects a change in particle geometry controlling Jeffery orbit and alignment sensitivity.

Shear-induced anisotropy is transferable only across cases that preserve the tested rotation, relaxation, and aspect-ratio regime.

4. Couplings that move the shear alignment

Shear history can align fibres while simultaneously changing dispersion and viscosity.

Confinement suppresses rotations and may bias orientation near walls.

Photocure freezes the instantaneous orientation distribution rather than an equilibrium state.

5. Failure signatures and false diagnoses

The diagnostic problem is not one generic failure but a choice among orientation relaxation during exposure delay, wall-induced orientation gradients and fibre aggregation or filtration in narrow gaps. Measurements of flow birefringence or polarised imaging where applicable, 2D/3D orientation tensors from microscopy, CT or transmission methods and rheometry with controlled shear history provide the evidence needed to keep those interpretations distinct. The value of Table 2 lies in contrast between rows. Mechanism selection uses the joint response rather than the largest individual signal.

Table 2. Failure-mode discrimination for shear-induced orientation.

Failure mode	Observable signature	Discriminating evidence
orientation relaxation during exposure delay	flow birefringence or polarised imaging where applicable	step shear followed by variable dark delay before cure
wall-induced orientation gradients	2D/3D orientation tensors from microscopy, CT or transmission methods	vary gap-to-fibre-length ratio
fibre aggregation or filtration in narrow gaps	rheometry with controlled shear history	compare continuous shear during illumination with pre-shear only
anisotropic shrinkage and stress caused by aligned reinforcement	mechanical tests along and across the programmed orientation	map orientation through thickness, not only at surfaces

6. Measuring shear alignment with traceable uncertainty

The minimum measurement set is the three observable columns represented in Table 2. Each is retained because it constrains a different failure pathway. An acceptable record for shear alignment must show separate monitoring of gelation timing without inferring it from independent resolution of Jeffery rotation and structural relaxation; during metrology of shear alignment, suspension interactions is resolved against gelation timing. In parallel, an uncertainty-controlled perturbation of suspension interactions probes the boundary condition most likely to change the interpretation, and the resulting uncertainty is carried forward explicitly; the uncertainty record for shear alignment keeps gelation timing separate from Jeffery rotation.

7. Experiments that discriminate competing mechanisms

Experimental discrimination is based on the pattern produced by the four Table 2 perturbations, not on ranking their signal amplitudes. Evidence for shear alignment is not accepted from a single nominal condition; during the causal challenge for shear alignment, gelation timing is tested against Jeffery rotation. The analysis requires a causal contrast between Jeffery rotation and suspension interactions, follows it with a replicate test of gelation timing, and uses a boundary challenge involving structural relaxation as a targeted challenge wherever the two indicate different mechanism or margin; the experiment for shear alignment separates Jeffery rotation from structural relaxation.

8. Model identification and validation for shear alignment

This avoids circular validation. [4] [1] [2,3] [5,6] Uncertainty remains explicit at the three Table 3 decisions instead of being absorbed into an empirical correction factor. Prediction against suspension interactions is the first stress test for shear alignment; only after that result is bounded is parameter estimation for Jeffery rotation and structural relaxation interpreted; within model identification for shear alignment, Jeffery rotation is not fitted through structural relaxation. The record keeps an uncertainty-bounded check on gelation timing outside that inference and reports it as an independent line of evidence; prediction for shear alignment keeps structural relaxation independent of suspension interactions.

9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for shear-induced orientation.

Decision	Minimum evidence	Acceptance logic
required shear rate and residence time for target anisotropy	For required shear rate and residence time for target anisotropy, document flow birefringence or polarised imaging where applicable over the full operating span and include a repeat series at the condition closest to the decision limit.	The candidate is acceptable when 'step shear followed by variable dark delay before cure' yields a repeatable flow birefringence or polarised imaging where applicable trend consistent with the qualified envelope and does not reveal orientation relaxation during exposure delay.
maximum exposure delay before orientation loss	Use calibrated 2D/3D orientation tensors from microscopy, CT or transmission methods measurements across the reference and candidate states to justify maximum exposure delay before orientation loss, with uncertainty propagated to the decision threshold.	The row passes where 'vary gap-to-fibre-length ratio' preserves the established 2D/3D orientation tensors from microscopy, CT or transmission methods relationship; detection of wall-induced orientation gradients marks failure of the decision.
whether confinement-induced gradients are acceptable for the application	The evidence floor for whether confinement-induced gradients are acceptable for the application is a repeatable rheometry with controlled shear history trend that spans the claimed envelope and includes the first departure from baseline behaviour.	The decision remains valid only if 'compare continuous shear during illumination with pre-shear only' gives a bounded, repeatable rheometry with controlled shear history response and does not produce fibre aggregation or filtration in narrow gaps.

Qualification of shear alignment treats tested ranges in Jeffery rotation and structural relaxation as one axis and an explicit transfer limit on gelation timing as another; inside the shear alignment envelope, structural relaxation and suspension interactions define different transfer limits. Between them, a separate boundary for suspension interactions supplies the deliberate challenge that determines whether the apparent transfer is mechanistic or merely coincidental; qualification of shear alignment bounds suspension interactions separately from gelation timing.

10. Design consequences for shear alignment

The design consequence is a three-part envelope defined by Table 3 rather than a single optimum or ranking. The design sequence uses an implementation check on suspension interactions to constrain a design change governed by Jeffery rotation; during design implementation for shear alignment, suspension interactions is constrained by gelation timing. Transfer is evaluated while maximum exposure delay before orientation loss is controlled independently, and a requalification trigger tied to gelation timing remains the explicit requalification trigger; the shear alignment design record separates gelation timing from Jeffery rotation. The design file records the boundary explicitly so later changes can be screened without row-order assumptions; implementation of shear alignment treats Jeffery rotation and structural relaxation as different control axes.

11. Evidence gaps for shear alignment

The first and third diagnostic channels are therefore the priority cross-checks in any extension campaign. For shear alignment, the evidence chain starts with scale transfer of Jeffery rotation; for unresolved shear alignment transfer, gelation timing is studied separately from Jeffery rotation. It then adds uncertainty in structural relaxation versus suspension interactions, while independent replication of gelation timing is retained as a separate control so the three sources of information cannot compensate silently; the evidence gap in shear alignment distinguishes Jeffery rotation from structural relaxation.

12. Qualification outcome for shear alignment

The accepted envelope is defined by the three Table 3 rows. Outside that envelope the review provides tests and hypotheses, not a qualified claim. The working sequence for shear alignment has three parts: agreement between measurement and prediction for Jeffery rotation; causal evidence that separates structural relaxation from suspension interactions; and a renewed-evidence trigger when gelation timing changes; at final qualification of shear alignment, Jeffery rotation is reconciled with structural relaxation. Each part answers a different engineering question, so uncertainty or failure in one part is not repaired by a favourable result in another; the closing shear alignment claim keeps structural relaxation distinct from suspension interactions.

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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.