

Formulation and Cure of Light-Curable Adhesives Across 2D, 2.5D and 3D Assemblies

Optical Access, Bondline Kinetics and Dark-Zone Control

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Statement of Significance

A light-curable adhesive is not qualified merely because an exposed bead becomes hard. In an assembly, the cure-driving spectrum must reach every location whose state matters, while interfacial chemistry, attenuation, oxygen, reaction after irradiation and geometrical shadowing can make the bondline non-uniform. ER-186 provides a bounded engineering framework for connecting formulation, optical access and time-dependent cure-state verification. It separates chemical cure evidence from structural-joint qualification and treats inaccessible or weakly illuminated regions as explicit process states rather than assumed extensions of the visible surface.

Abstract

Light-curable adhesives combine rapid, addressable processing with a demanding dependence on optical access. The delivered cure state is governed by source spectrum, irradiance history, substrate transmission, formulation absorption and scattering, bondline thickness, interfacial conditions and post-irradiation reaction. Direct primary evidence shows that staged UV curing can create interval-dependent weak boundaries in a defined acrylate optical assembly; that a UV adhesive can continue reacting and relaxing after irradiation in a studied system; and that reaction heat and cure-dependent viscoelastic response can influence predicted cure-shrinkage stress [1-3]. A separate cyanoacrylate study demonstrates the value of measuring interfacial and bulk bondline reaction independently as functions of depth and time, but is used only as a metrology analogue [4]. ER-186 converts these observations into conservative qualification logic for nominally planar, partially enclosed and volumetrically obstructed assemblies. No universal wavelength, exposure, interval, depth, temperature, conversion or strength criterion is proposed. A secondary cure is accepted only when its initiation route and reach are demonstrated for the actual formulation and geometry.

Keywords: light-curable adhesive; UV adhesive; bondline; optical access; cure kinetics; dark reaction; oxygen inhibition; cure-state verification

1. Scope and ownership

ER-186 addresses formulation and cure control for light-curable adhesives used in assemblies with different degrees of optical accessibility. For this review, 2D denotes a nominally planar, directly exposed bondline; 2.5D denotes a partly enclosed or edge-accessible bondline with a limited optical path; and 3D denotes an assembly in which curvature, depth, intervening materials or components create spatially varying access. These labels describe optical topology, not manufacturing standards.

Within the named sub-series *Radiation Curing Beyond Additive Manufacturing*, ER-186 examines the same photochemistry, oxygen-inhibition, attenuation, interfacial and qualification principles in adhesive bondlines rather than only in printed layers. It does not extend its evidence or claims to films, coatings or inks outside the bondline systems addressed here.

The review owns source-formulation spectral matching, transmission through substrates, depth- and time-dependent bondline reaction, staged cure, post-irradiation reaction, dark or shadow zones, bounded secondary-cure strategies and cure-state verification. It does not own adherend design, overlap geometry, load-path design, mechanical test selection or structural failure qualification. ER-165 retains adhesive

bonding and structural joining of printed photopolymers; where the substrate is a printed photopolymer, ER-165 governs and ER-186 defers. ER-190 retains controlled undercure, the conversion window, residual unsaturation as a specification and migration from a permanently soft layer.

The evidence core contains one full primary article on a staged acrylate UV-adhesive assembly, two primary UV-adhesive conference abstracts and one complete abstract on depth-resolved Raman monitoring of a non-photocured cyanoacrylate bondline [1-4]. The last source is method evidence only. All formulations, geometries, times and outcomes remain study-specific.

2. A bondline is a delivered-energy and reaction field

The relevant process variable is not the source setting alone. A useful conceptual description is

$$H_{\lambda}(x,y,z,t) = \int_0^t E_{\lambda,0}(\tau) T_{\lambda}(x,y,z,\tau) d\tau$$

where the local spectral radiant exposure, H_{λ} , depends on the incident spectral irradiance history, $E_{\lambda,0}$, and an assembly-specific spectral transfer term, T_{λ} . Its time dependence allows the transfer to change during exposure as initiator is consumed and the developing network alters absorption or scattering. The transfer term can also incorporate source angle, distance, intervening-substrate transmission, adhesive absorption, reflection and shadowing. It is a bookkeeping model, not a universal cure equation.

Chemical reaction then depends on local initiation, oxygen and other inhibitors, mobility, temperature and the developing network. Two locations that receive the same broadband meter reading outside the assembly may therefore reach different cure states. Conversely, locations with different exposure histories can sometimes converge during post-irradiation reaction, but that convergence must be measured rather than assumed.

3. Formulation and source must be matched spectrally

A declared lamp family or nominal wavelength is insufficient to specify cure. The source spectrum must be considered together with the absorption response of the complete adhesive, including photoinitiator, sensitiser, monomers, oligomers, pigments, fillers, stabilisers and any species generated during exposure. A substrate that appears transparent to the eye may attenuate the initiating band, while a clear adhesive can still absorb strongly through depth.

Qualification should therefore record the source spectrum or a traceable spectral description, irradiance at a declared plane, exposure time or motion history, optical path, substrate identity and thickness, adhesive lot and bondline thickness. If the source, substrate, adhesive or geometry changes, retained measurements must be able to detect the resulting shift in local cure state.

No universal wavelength or radiant-exposure minimum follows from the present evidence set.

4. Optical access changes from 2D to 3D assemblies

In a directly exposed planar bondline, cure may still vary through thickness and near interfaces, but access can usually be mapped from one principal direction. A 2.5D assembly adds edges, recesses, opaque masks or partial enclosure. A 3D assembly adds multiple path lengths and shadowing bodies, so source visibility and transmitted spectrum can change over short distances.

The engineering consequence is that a cure procedure must be tied to an optical-access map. The map should distinguish directly illuminated regions, regions reached through a substrate, regions reached only by scattering or reflection, edge-access regions and locations with no demonstrated initiating path. A region is not qualified as light-cured merely because it is adjacent to a cured region.

Multiple source directions, rotation or staged exposure may improve access, but their effectiveness depends on the actual assembly. Ray visibility alone does not prove sufficient spectral energy after attenuation, and a surface dosimeter does not automatically represent a buried bondline.

5. Interface and bulk bondline states can differ

The bondline should not be treated as a spatial average when interfacial performance matters. Raheem et al. used confocal Raman microscopy to follow ethyl cyanoacrylate polymerisation as a function of both time and bond depth and to distinguish substrate-interface behaviour from the bulk region [4]. Their chemistry is not photoinitiated, so their substrate-specific kinetics cannot be transferred to light-curable adhesives. The transferable lesson is metrological: spatially separated reaction histories can be measured rather than inferred from a bulk endpoint.

For a light-curable adhesive, an interface may differ from the bondline centre because of substrate transmission, surface chemistry, contamination, adsorbed moisture, oxygen access, local heat transfer or constrained mobility. A bulk conversion measure can therefore miss an under-reacted interface, and an apparently cured edge can miss an inaccessible interior.

Verification should sample the locations linked to the failure hypothesis. Methods may include depth-resolved or sectioned spectroscopy, microhardness mapping, extraction at defined locations, thermal or viscoelastic analysis, microscopy and application-specific witness specimens. Each method needs a declared spatial resolution and detection limit.

6. Staged exposure creates a controlled interface between cure histories

Staged curing can be necessary when an assembly must be positioned, fixed and then completed, or when more adhesive is added after an initial exposure. It also creates a boundary between material states.

Xing et al. studied one acrylate UV adhesive in a thin optical-coupling assembly and found that increasing the interval between initial and final exposure was associated with weaker tensile, shear and shock results and with an oxygen-associated, incompletely cured weak boundary in that system [1]. The study supplies direct evidence that the interval is a process variable and that a later exposure does not necessarily erase the history of an exposed intermediate surface.

The study-specific time limits, layer thickness, source conditions and strengths are not ER-186 recommendations. A different radical, cationic, hybrid or thiol-based formulation can respond differently. The defensible rule is to control interval duration, atmosphere, surface exposure, contamination opportunity, temperature and the state at which the next adhesive increment or assembly operation occurs.

7. Irradiation can end before reaction and relaxation end

The end of illumination is not necessarily the end of material evolution. Otani et al. reported dynamic mechanical measurements during continuous UV irradiation and a subsequent dark-reaction period in a UV adhesive; reaction continued after irradiation at a slower rate in the studied system, and relaxation behaviour was linked to cure degree [2]. Yamamoto et al. separately incorporated measured reaction heat and cure-dependent shift factors into a UV-adhesive shrinkage-stress analysis [3].

These abstract-level results support a process distinction among lamp-off time, chemical conversion, thermal equilibration, stress development and handling readiness. They do not supply a universal dark-reaction allowance, gel point, cooling time or stress model.

A qualification record should define when each endpoint is measured. Immediate handling, delayed assembly, post-cure inspection and final service acceptance may correspond to different material states even when no additional light is delivered.

8. Dark and shadow zones require an explicit cure mechanism

A dark zone is a location with no demonstrated initiating spectral exposure. A shadow zone receives less or spectrally altered exposure than the qualified reference. These states should not be grouped merely because both are difficult to see.

Possible controls include redesigning the optical path, changing source direction, using a transmitting adherend, reducing attenuation, exposing before closure, applying a validated secondary source or using a genuinely dual-initiation formulation. Each option changes the material-process system and must be qualified.

Migration of radicals or heat from an illuminated region is not a general cure guarantee. Nor does a manufacturer label such as “dual cure” establish reach, kinetics or final network state in the assembly. The secondary mechanism must be activated under the actual temperature, humidity, mixing, catalyst, moisture or chemical conditions required by that formulation, and its compatibility with the light-cured region must be demonstrated.

9. Secondary-cure rescue is a requalification event

Adding a thermal, moisture, redox, anaerobic or other secondary route can rescue optically inaccessible regions only if it creates the required state without unacceptable gradients or interfaces. It may also change shelf life, mixing sensitivity, exotherm, latency, residual chemistry, shrinkage, modulus or ageing.

A bounded rescue evaluation should:

1. define the geometrical region that the light route cannot qualify;
2. identify the secondary initiation mechanism and its necessary environmental conditions;
3. measure cure state separately in light-dominant, secondary-dominant and transition regions;
4. check the timing interaction between the two routes;
5. compare residual chemistry and functional response in the final assembly;
6. define storage, application and change-control limits.

This is qualification logic proposed by ER-186, not a universal protocol derived from the four sources.

10. Cure-state verification must be claim-specific

“Cured” can mean different things: loss of tack, sufficient conversion, a specified modulus, bounded soluble fraction, acceptable residual chemistry, adequate adhesion or survival of a service test. These are not interchangeable.

A useful verification stack separates:

1. delivered optical exposure at representative paths;
2. chemical reaction state at interfaces and through depth;
3. thermal and viscoelastic state at the declared measurement time;
4. residual or extractable profile relevant to intended use;
5. functional performance of the actual assembly.

Raheem et al. support separate interface and bulk measurement as a general analytical concept [4]. Xing et al. show why interfacial chemical evidence and mechanical response can both be needed in a staged UV process [1]. Otani et al. and Yamamoto et al. support time- and cure-dependent mechanical-state considerations [2,3]. None of these sources establishes that a single method qualifies every endpoint.

11. Chemical cure evidence is not structural-joint qualification

A conversion map can show whether selected functional groups reacted under a declared method. It cannot by itself qualify adherend preparation, bond geometry, defects, load transfer, environmental durability or failure mode. Similarly, a mechanical result from one optical device does not become a design value for another assembly.

ER-186 therefore ends at the material-process interface. It can specify that relevant bondline locations require demonstrated cure state and can identify process variables that threaten that state. Structural acceptance criteria, specimen geometry, loading, statistical basis and durability remain in the applicable joint-qualification programme, including ER-165 where printed substrates are involved.

12. Failure modes and discriminating checks

An underperforming light-cured bond can result from spectral mismatch, insufficient transmission, excessive thickness, shadowing, oxygen exposure, contamination, a staged-cure weak boundary, incomplete secondary initiation, thermal history or a structural-joint problem. Similar symptoms can arise from different mechanisms.

A tacky exposed surface suggests a different investigation from a dry edge with an under-reacted buried interface. A delayed strength change may reflect post-irradiation reaction or physical relaxation. Interfacial failure after staged application may require chemical mapping of the intermediate surface, while cohesive failure in an inaccessible volume may require depth-resolved cure analysis.

The test plan should discriminate among the credible causes. Increasing exposure without locating the deficient region can overprocess accessible regions while leaving a fully blocked location unchanged.

13. Change control

Potential requalification triggers include photoinitiator or sensitiser identity and concentration, monomer or oligomer composition, inhibitor, pigment, filler, adhesive lot, storage history, bondline thickness, dispensing path, substrate material or thickness, surface preparation, source spectrum, irradiance, distance, angle, exposure time, motion, source ageing, interval between stages, atmosphere, temperature, assembly sequence and secondary-cure conditions.

Not every change requires a complete restart. A bridging argument is acceptable when retained measurements are sensitive to the affected optical, chemical and functional failure modes. A nominally unchanged lamp setting is not a bridge if the substrate, bondline or formulation changed the delivered spectrum.

14. Minimum reporting

A reusable cure record should identify the adhesive formulation and lot state, storage and conditioning, substrate identities and thicknesses, surface preparation, bondline geometry and thickness, assembly sequence, source and spectrum, irradiance-measurement plane, exposure history, source-to-assembly geometry, atmosphere, temperature, staged-cure intervals, secondary-cure conditions, measurement times and the spatial locations of cure-state tests.

The report should distinguish direct measurement from modelled optical transfer and from assumption. It should state which locations were not measured, which endpoint defines acceptance and which structural or service claims remain outside the cure evidence.

15. Evidence limitations

The evidence core is sufficient for a bounded engineering review, not a systematic comparison of adhesive chemistries or cure equipment. Only one source is a full direct primary article on an acrylate UV-adhesive assembly. Two direct UV-adhesive sources are available at abstract depth, and the depth-resolved Raman source uses non-photocured cyanoacrylate chemistry [1-4].

The evidence does not establish universal wavelengths, exposures, bondline depths, stage intervals, dark-reaction periods, temperatures, conversion targets, stresses or strengths. It does not validate a specific dual-cure adhesive, a universal shadow-zone remedy or any safety or regulatory claim.

16. Conclusions

Light-curable adhesive qualification is an assembly problem. Source spectrum, substrate transmission, formulation attenuation, bondline thickness, interfaces, geometry and time together create a spatially varying material state.

Direct evidence shows that a staged UV-adhesive process can retain an interval-dependent interfacial history [1], that reaction and relaxation can continue after irradiation in a studied UV adhesive [2], and that reaction heat and cure-dependent response can matter to stress analysis [3]. Depth-resolved bondline measurement is

analytically feasible, although the controlled example uses cyanoacrylate and is not direct photochemical evidence [4].

The defensible control rule is therefore explicit: map optical access, measure the cure state at locations tied to failure risk, control the interval and environment between stages, and requalify any secondary cure route. Surface hardness, source settings or bulk conversion alone do not establish complete bondline cure, and chemical cure evidence does not replace structural-joint qualification.

Related Engineering Review boundaries

ER-186 owns formulation and cure control for light-curable adhesive bondlines under restricted optical access. ER-165 retains adhesive bonding and structural joining of printed photopolymers. ER-190 retains controlled undercure, the conversion window, residual unsaturation as a specification and migration from a permanently soft layer. ER-083 and ER-084 retain general photocuring taxonomies; ER-170 retains accelerated ageing and life-claim validity; ER-177 retains exposure verification in industrial photopolymer operations; and ER-091 to ER-095 retain their applicable safety and regulatory scopes.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. This review does not claim that any 3Dresyns adhesive, resin or process is qualified for a specific assembly, structural joint, medical, food-contact or regulated use.

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Data availability

No new experimental dataset was generated for this review.