

Adhesive Bonding and Structural Joining of Printed Photopolymers

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Abstract

A bonded joint on a printed photopolymer is usually described by a single number in megapascals, and that number is usually a property of the wrong thing. This review treats the joining of vat-photopolymerised components as a problem in which the adherend, not the adhesive, is most often the limiting element, and in which the adherend arrives at the bond line in a state that the printing workflow has determined and that almost nobody records. The controlling variables are the post-cure state, the oxygen-inhibited free surface, the wash-solvent history and the layer geometry — every one of which is set upstream of the joining operation and none of which appears in a conventional adhesive specification. The literature supports this framing convergently: across processes and laboratories, printed adherends tend to fail before the bond line does. It also fails to support the quantitative claims most often made from it. **This review located no verified structural lap-shear study of a vat-photopolymer-to-vat-photopolymer adhesively bonded joint, no study connecting the oxygen-inhibited surface layer to joint strength, and no study connecting wash-solvent residue to joint strength, although both are known to change the substrate.** The usable quantitative evidence is dental shear-bond-strength data whose test geometry makes it non-comparable with engineering lap-shear values. This review therefore separates what is established, what is bounded by analogy from other additive processes, and what must be generated locally, and specifies a joining qualification architecture built around determining the failure locus rather than reporting a strength.

1. Objective and scope

The objective is to provide a factory-facing framework for joining vat-photopolymerised components and for defending the resulting joint as a structural element.

ER-165 governs whenever the principal engineering question is **how to join a printed photopolymer component**: the substrate state before joining, surface preparation, adhesive selection against service state, bond-line geometry and cure access, determination of the failure locus, environmental durability, and joint qualification and change control.

Corpus ownership. ER-073 owns interlayer cohesion and mechanical anisotropy of the printed part itself [28]. Where a joint fails in the adherend — which this review shows is the common case — the governing evidence is ER-073's, and ER-165's contribution is to require that the locus be determined and reported rather than to re-derive adherend strength. ER-033 owns washing- and drying-induced extraction, property change and dimensional response [29]; the wash state of the surface being bonded is its subject, and ER-165 owns the consequence of that state for adhesion. ER-030 owns oxygen inhibition and free-surface cure [30]; the inhibited layer is its subject, and ER-165 owns whether that layer must be removed before bonding. ER-053 owns build-platform adhesion [31] — a different interface and a different question. ER-013 owns self-healing and interlayer repair [32] and is excluded entirely.

Two forward boundaries are stated because the papers do not yet exist. **ER-186 will own the formulation and cure of light-curable adhesives**; ER-165 selects and qualifies an adhesive but does not formulate one, and treats the dark-zone problem as an optical-access constraint on joint design rather than as a cure-chemistry problem. **ER-181 will own post-cure process engineering**; ER-165 treats post-cure state as an input variable, not as a process to design.

Excluded: interlayer cohesion as the main subject; self-healing; build-platform adhesion; adhesive formulation as the principal subject.

The review covers the process category defined as vat photopolymerization in ISO/ASTM 52900:2021 [8]. Evidence from other additive processes is used only as declared contrast and is labelled as such at every occurrence.

2. The adherend arrives in a state the joining operation did not choose

A conventional adhesive specification assumes a substrate whose surface is a material property. A printed photopolymer surface is not: it is an output of the print, wash and post-cure workflow, and it differs from itself between two parts made on the same machine on the same day under different post-processing.

Four state variables govern, and they are set before the joint is designed.

Degree of cure and post-cure history. The network the adhesive bonds to is not fully converted at the moment of printing, and post-cure changes it substantially. This is developed against measured evidence in §3.

The oxygen-inhibited free surface. A free surface cured in air carries an under-converted, monomer-rich, frequently tacky layer whose formation is ER-030's subject [30]. Whether that layer must be removed before bonding, and what it costs if it is not, has **no located primary evidence**. This is the largest single gap in this review and is stated again in §10.

Wash-solvent history. Liu and co-workers established on a digital-light-processing water-washable resin that the washing agent and duration change the printed part itself: flexural strength of the cured control was 110.31 ± 5.55 MPa, falling to 64.30 ± 14.50 MPa after alcohol washing and to 69.53 ± 14.75 MPa after 30 minutes of washing; degree of conversion peaked at 53.94 ± 1.40 % at 20 minutes for water and detergent against 42.42 ± 2.21 % for alcohol at 30 minutes; and TEGDMA at 135 ppm was detected only in the unwashed group, all washed groups falling below detection [15]. **That study measures the part, not a joint.** Nobody has connected wash state to bond strength, although it demonstrably changes both the surface chemistry and the bulk properties of the thing being bonded.

Layer geometry. Zwicky and co-workers isolated layer thickness as a bond-strength determinant on four photopolymerised dental resins across polished, 20, 50 and 100 μm layer conditions, with and without silica-coating air abrasion, dry and after 5 000 thermocycles, at $N = 1280$. Roughness increased with layer thickness; material and layer thickness both significantly affected shear bond strength; silica coating mainly benefited polished surfaces [18]. This is the only located study isolating a build parameter as a determinant of adhesion on a vat-photopolymer adherend.

Consequence for specification. A joining specification that names an adhesive and a surface preparation but does not name the post-cure route, the wash agent and duration, and the layer thickness has not specified the joint. Two parts differing only in wash solvent are, for bonding purposes, two different substrates.

3. Post-cure changes the adherend more than most surface treatments change the interface

Riccio and co-workers measured twelve methacrylate resins printed by stereolithography before and after post-cure and reported that Young's modulus rose by **88 % on average** across the resin set, with a maximum of +215 % and a minimum of +33 %, and tensile strength by **89 % on average**, maximum +172 %, minimum +29 %, while ductility fell — elongation at break dropping by up to 90 % in one resin [21].

Two consequences follow for joining, and the second is the one usually missed.

The first is that the adherend's capacity to survive the joint is set by post-cure. If the failure locus is in the adherend, then post-cure state — not adhesive selection — is the dominant lever on joint strength.

The second is that post-cure removes the plasticity that lets a bonded region redistribute stress. A stiffer, stronger, less ductile adherend concentrates load at the ends of an overlap rather than yielding to spread it. **Post-cure therefore does not simply improve the joint; it changes which failure mode governs.** This is stated as an inference from [21] and is not measured there; no located study varies post-cure state and measures joint strength on a vat-photopolymer adherend. It is offered as a hypothesis to be tested, not as a result.

4. Surface preparation: what the evidence actually supports

The surface-preparation literature on vat-photopolymer adherends is dental, is small, and is more consistent than its size suggests.

Mechanical abrasion is the only treatment with durable support. Kang and co-workers bonded resin cements to a digital-light-processing urethane-dimethacrylate resin and a stereolithography Bis-EMA resin, with and without airborne-particle abrasion and

a universal adhesive, and aged the specimens through 10 000 thermocycles between 5 and 55 °C in distilled water. Abraded groups with adhesive and cement retained strength across ageing — 24.7 ± 4.9 MPa before and 22.5 ± 3.3 MPa after thermocycling in the strongest configuration — while the untreated group with cement alone **collapsed to 8.1 ± 3.1 MPa after thermocycling** [14]. The second resin, the stereolithography Bis-EMA system, was largely insensitive to adhesion condition and declined across the board after ageing.

The magnitude of that collapse is the important part. Without mechanical abrasion, the joint lost roughly two-thirds of its strength in water thermocycling. Adhesion that survives dry testing and fails on ageing is the characteristic failure of an untreated printed surface.

Htat and co-workers reached the same conclusion on a different geometry, comparing airborne-particle abrasion, tetrahydrofuran conditioning and a bonding agent on digital-light-processing denture bases: abrasion significantly increased bond strength across all base materials, and tetrahydrofuran underperformed it [16].

Plasma helps immediately and does not survive ageing alone. Lee and co-workers compared vacuum plasma against airborne-particle abrasion with and without a bonding agent, before and after thermocycling. The highest group — plasma with bonding agent, before thermocycling — reached 23.9 ± 2.2 MPa, and water wettability improved after plasma, but **plasma-alone groups degraded significantly after thermocycling** [13].

The meta-analytic position agrees, and reveals how thin the base is. Bourgi and co-workers searched five databases to February 2025 for surface treatments on three-dimensionally printed resins and found **only nine studies meeting inclusion, eight entering meta-analysis**. Surface treatment significantly improved immediate bond strength; individually, **only sandblasting and silane were significant**, and after ageing **only sandblasting and hydrofluoric acid** remained significant. Plasma and laser were not meta-analysable [19]. The authors note heterogeneous resin compositions, non-standardised ageing and no formal publication-bias assessment. The review also states that not all included studies were vat photopolymerisation.

Nine studies is the finding. An entire surface-preparation practice for a growing manufacturing route rests on a body of work small enough to read in an afternoon.

Standards do not cover this surface. ASTM D2093-03(2025) covers preparation of plastics prior to adhesive bonding — sanding, solvent wiping, chemical treatments — and self-limits by stating that it does not address all available methods [7]. It predates additive manufacturing and contains nothing on oxygen-inhibited layers, residual monomer or isopropanol wash residue. ISO 17212:2012 guides surface preparation of metals and plastics before bonding and likewise contains nothing on additively manufactured or photopolymer surfaces [6].

5. The failure locus is the result; the strength is a by-product

The most robust finding available across the whole joining literature for printed polymers is convergent across processes, laboratories and joint geometries: **the printed adherend tends to fail before the bond line does**.

On vat photopolymers: Htat and co-workers found that control heat-polymerised and milled denture bases failed **90 % adhesively**, whereas the digital-light-processing printed bases failed **predominantly cohesively regardless of treatment** — that is, in the adherend [16]. Grgić and co-workers, print-bonding woven fabric into an LCD-printed photopolymer and testing to EN ISO 4587, found that **all 45 specimens failed in the textile adherend**, at 1.38 ± 0.04 MPa with a coefficient of variation of about 3.1 % and no significant effect of layer thickness or exposure by two-way analysis of variance [9]. That configuration is photopolymer-to-textile print-to-bond, not an adhesively bonded photopolymer-to-photopolymer joint, and is cited for its failure-locus result only.

On other additive processes, declared here as contrast: Spaggiari and Denti found on material-extrusion adherends across seven surface morphologies that morphology played only a minor role because it cannot provide mechanical interlocking under peel, and that failures were predominantly substrate failure at corner stress concentrations [24]. Ribeiro and co-workers found in scarf joints on filament-printed PLA, ABS and PETG that **adherend failure dominated ABS and PETG regardless of adhesive**, while PLA with a stiff epoxy failed cohesively in the adhesive at 4.16 ± 0.18 kN against 2.39 ± 0.11 kN for a tougher polyurethane at 10 mm bond length [23]. Frascio and co-workers found on fused-filament ABS that **plasma treatment was necessary to move the failure locus from the interface into the adherends** [22].

The engineering consequence is a rule about interpretation. When a printed adherend fails, the measured value is a lower bound on what the adhesive could have carried and an upper bound on what the adherend can carry. It is not a bond strength. Reporting it as one — and then comparing it against a different adhesive tested on a different adherend — compares two adherends.

Failure-mode designation must therefore be part of the result, not a remark. ISO 10365:2022 designates main failure patterns and applies to mechanical testing of bonded assemblies regardless of adherend and adhesive material [5], which makes it the defensible scheme here. ASTM D5573-99(2019) classifies failure modes in fibre-reinforced-plastic joints [3]; its fibre-tear categories have no analogue in an unfilled photopolymer, so it maps only partially. **Not one located study applies either designation to a vat-photopolymer adherend;** the dental studies use ad hoc adhesive/cohesive/mixed schemes, which is why cross-study comparison is currently unsafe.

6. Test geometry, and why the available numbers cannot be pooled

Two families of number appear in this literature and they are not commensurable.

Dental shear bond strength is measured by loading a small bonded button or cylinder in shear. The stress field is highly non-uniform and the value depends strongly on specimen geometry and loading fixture. Kang [14], Lee [13], Zwicky [18], Albahri [17] and Ersöz [12] report in this family.

Engineering lap-shear strength is measured on a single-lap joint in tension. ASTM D3163-01(2023) is the correct standard for rigid plastic adherends [2]; ISO 4587:2003 is the ISO equivalent for rigid-to-rigid bonded assemblies [4]. **ASTM D1002 is metal-to-metal only** by its own title and scope [1] and is routinely mis-cited for printed-polymer adherends.

Both standards state that the apparent value is not suitable as a design allowable. That caution is doubled here, for a reason specific to this material class: **ASTM D3163 states, in its Significance and Use clause 4.2, that it “is not intended for use on anisotropic adherends such as reinforced plastic laminates”** [2]. A layered vat-photopolymerised part is measurably anisotropic — anisotropy is ER-073’s subject [28] — so the standard most nearly applicable to this joint declares itself unsuited to a property the adherend has. The exclusion sits in clause 4.2 and not in the standard’s Scope clause, which is where a reader would look for it.

Rule for this corpus: dental shear-bond-strength values and lap-shear values must never appear in the same table. They answer different questions with different stress fields, and tabulating them together manufactures a comparison that no experiment performed.

7. Cure access, dark zones and the optical-access constraint

Light-curable adhesives are attractive for photopolymer assemblies because the chemistry is compatible and the cure is fast. They introduce a constraint that adhesives for opaque adherends do not have: **the cure requires photons to reach the bond line.**

No peer-reviewed primary source addressing shadowed bond lines and dark-zone cure on printed photopolymer assemblies was located. Everything returned on the subject was supplier literature, which is not independent evidence for mechanism or performance.

One verified engineering response exists, and it is architectural rather than chemical. Lee and co-workers bonded a digital-light-processing printed open-channel chip to a **transparent PMMA cover**, using vacuum-assisted removal of channel-filling adhesive, and achieved burst strength above 869 kPa with channel cross-section reduction below 6 % on a working channel of $76.1 \times 50.9 \mu\text{m}^2$ [10]. The transparent counterface is the mechanism: cure light is delivered through the part that transmits it, not through the part that does not.

Escriba-Flores and co-workers developed dual-curing acrylic/epoxy systems for digital light processing and used the latent epoxy stage to bond printed parts, explicitly for fabricating large parts through bonding, reporting modulus from 3 to 2500 MPa and maximum tensile strength of 80 MPa for the material [11]. **The joint test method, standard and quantitative joint strengths were not obtainable for this review and no joint value is attributed here.** This is the closest located approach to a structural vat-photopolymer-to-vat-photopolymer joining system and its full text should be obtained.

Design rule this supports. For a light-cured bond line, optical access is a joint design variable of the same rank as bond area. Either one adherend transmits at the adhesive’s activation wavelength, or the adhesive must have a non-optical secondary cure mechanism, or the bond line must be exposed before closure. A joint that relies on light reaching a shadowed region through an absorbing pigmented photopolymer has an uncontrolled cure state and cannot be qualified by strength testing alone, because the test coupon and the production part will not shadow identically.

8. Environmental durability

The durability evidence is confined to dental water thermocycling. Kang and co-workers applied 10 000 cycles between 5 and 55 °C [14], Zwicky and co-workers 5 000 cycles [18], and Lee and co-workers thermocycled plasma-treated groups [13]. Within that envelope the results are consistent and useful: mechanical abrasion survives ageing, chemical and plasma treatments alone frequently do not, and untreated surfaces lose most of their strength.

Outside that envelope this review found nothing. **No humidity, elevated-temperature or fluid-exposure durability data on structurally bonded vat-photopolymer joints was located.** A joint intended for sustained load at elevated temperature, or for contact with a service fluid, has no published durability basis and requires locally generated evidence.

One further caution belongs here. Thermocycling in water is an ageing protocol designed for the oral environment. It couples thermal cycling with water uptake, and a printed photopolymer's water uptake is itself state-dependent — a property that falls under ER-033's subject [29]. Transferring a thermocycling result to a dry industrial duty overstates its relevance in one direction; transferring it to a wet high-temperature duty understates the exposure in the other.

9. Solvent welding

Solvent welding joins thermoplastics by locally dissolving the surface and allowing chains to interdiffuse and re-entangle across the interface. **That specific mechanism cannot be presumed to transfer to a crosslinked vat-photopolymer network**, in which a good solvent produces swelling rather than dissolution and in which chain interdiffusion across the interface is not available. **This review makes the narrow claim and not the wide one: it does not assert that every solvent-mediated joining mechanism is impossible in a photopolymer, only that the dissolution-and-interdiffusion mechanism on which thermoplastic solvent welding rests is unavailable, and that no substitute mechanism has been demonstrated.**

The evidence position is an absence. **This review located no primary evidence validating solvent welding as a structural joining route for a cured vat-photopolymer network.** The single verified chemical-conditioning datapoint is tetrahydrofuran on digital-light-processing denture bases, where it underperformed airborne-particle abrasion [16].

Position: any solvent-welding claim for a printed photopolymer should be treated as unsupported unless accompanied by primary evidence for the specific resin — which is a statement about the evidence, not a prohibition derived from theory. Solvent conditioning as a *surface preparation* — swelling to increase adhesive penetration — is a different proposition and is weakly supported at best by [16].

10. Evidence gaps stated as gaps

These are the places where the practice has run ahead of the evidence. They are listed because a specification that assumes any of them is assuming something nobody has measured.

No verified structural lap-shear study of a vat-photopolymer-to-vat-photopolymer adhesively bonded joint. The engineering-side additive bonding studies located whose process could be verified use material extrusion [22,23,24] or multi-jet fusion [25]; for two further located studies the additive process could not be verified and is not asserted here [20,27]. The nearest vat-photopolymer candidate reports joint work without an accessible method or number [11]. This is the central gap.

Oxygen-inhibited layer to bond strength: no located evidence. The inhibited surface is well established as a phenomenon [30]; this review located no measurement of its effect on adhesion on a printed adherend.

Wash-solvent residue to joint strength: no located evidence. Wash agent and duration demonstrably change the substrate [15]; this review located no study connecting that to a bond.

Light-curable adhesives and dark zones: no peer-reviewed primary source. The only verified engineering response is to bond through a transparent counterface [10].

Build orientation to bonded joint strength on vat photopolymers: no located evidence. Layer thickness has been isolated [18]; this review located no equivalent study isolating orientation.

Failure-mode reporting is not standardised in this literature. This review located no study applying ISO 10365 [5] or ASTM D5573 [3] designations to a vat-photopolymer adherend.

Durability beyond dental thermocycling: none.

The dental and engineering value families are not comparable and must not be pooled, as set out in §6.

11. A proposed joining qualification architecture

This architecture is a proposed engineering qualification framework, offered for use where no application-specific validated procedure exists. No standard establishes it and none is claimed for it; it is the writer's construction over the evidence state set out in §10, and a reviewer or a duty holder may reasonably replace it. Where a gate below restates a requirement that a cited standard or source directly establishes, that source is named at the gate; everything else is proposal.

Within that framing, the gates are the minimum this review proposes for a bonded joint on a printed photopolymer to be defensible, in the state-resolved form ER-139 requires [33]. Each is intended to close on evidence rather than on a supplier statement.

Gate	Question that must close	Minimum evidence	Stop condition
J1 — adherend state	In what state does the adherend reach the bond line?	Declared post-cure route, wash agent and duration, layer thickness, orientation, storage interval	Substrate treated as a material constant
J2 — surface condition	Is the oxygen-inhibited or residue-bearing surface removed, and how is that verified?	Stated preparation with a verification method; abrasion has the only durable support [14,16,19]	Preparation assumed effective without ageing evidence
J3 — adhesive compatibility	Is the adhesive compatible with this resin chemistry in the service state?	Compatibility evidence on the actual resin, not on a generic plastic	Datasheet compatibility class used as evidence
J4 — cure access	Do photons or the secondary cure mechanism reach the whole bond line in the production geometry?	Optical-access argument for the production part, not the coupon [10]	Coupon cure used to justify a shadowed production joint
J5 — bond-line geometry	Are overlap, thickness and fillet defined and controlled?	Dimensioned bond line with tolerance	Bond line set by assembly
J6 — failure locus	Where does the joint fail?	ISO 10365 designation [5] on every specimen, reported with the strength	Strength reported without failure mode
J7 — adherend-limited check	If failure is in the adherend, has the adherend been qualified for that load?	Cross-reference to ER-073 [28]; joint value declared as an adherend bound	Adherend failure reported as bond strength
J8 — durability	Does the joint survive the service environment, not a proxy for it?	Ageing in the actual exposure; thermocycling only if water at 5–55 °C is the duty [13,14,18]	Dental thermocycling used to qualify an industrial duty

Gate	Question that must close	Minimum evidence	Stop condition
J9 — change control	What change invalidates this qualification?	Named: resin, post-cure route, wash chemistry and duration, layer thickness, orientation, adhesive lot, surface preparation, bond-line geometry	Requalification by judgement

Gate J6 is the one that converts a number into evidence. Gate J1 is the one that is almost universally omitted.

12. Failure modes of the joining programme itself

Reporting a strength without a locus. The most common failure, and the one that makes the resulting number uninterpretable.

Treating the printed surface as a material property. Two parts with different wash histories are different substrates [15].

Qualifying dry and serving wet. Untreated surfaces have been observed to lose roughly two-thirds of their strength on water thermocycling [14].

Pooling incommensurable values. Dental shear-bond-strength and lap-shear values in one table [§6].

Citing a metal-to-metal standard. ASTM D1002 is metal-to-metal by scope [1]; D3163 is the rigid-plastics method [2], and its clause 4.2 declares it not intended for anisotropic adherends.

Transferring an extrusion result. Material-extrusion adherends fail through raster and weld-line networks; a vat-photopolymer adherend has neither. The cited non-vat-photopolymerisation contrast [20,22,23,24,25,27] bounds expectation and does not qualify a joint.

Assuming cure reached the bond line. A light-cured joint whose production geometry shadows differently from its coupon has an unqualified cure state [§7].

13. Limitations of this review

This review does not qualify any adhesive for any resin or duty. The quantitative evidence available for vat-photopolymer adherends is almost entirely dental, uses a shear-bond-strength geometry that is not comparable with engineering lap-shear testing, and comprises — on the meta-analytic count — nine studies [19].

Findings are attributed only to sources whose content was read. Sources located during discovery but not used as evidence are nonetheless listed in the references and identified here, so that the reference list is a complete record of what was found rather than only of what was used; a reviewer who prefers the opposite convention should say so and they will be removed.

Ersöz and co-workers [12], Yildirim-Manav and co-workers [26] and Sedlacek and co-workers [25] are cited for topic only, with no finding attributed; their content was not obtained. For Kovan and co-workers [20] and Ribeiro and co-workers [27] the additive process was not verified and is not asserted. The joint values in Escriba-Flores and co-workers [11] were not obtainable and none is quoted.

The inference in §3 that post-cure changes which failure mode governs is a hypothesis derived from measured material-property changes [21], not a measured joint result.

14. Conclusions and research priorities

The adherend is usually the limiting element. Across processes and laboratories, printed adherends tend to fail before the bond line [9,16,22,23,24].

Consequently a reported bond strength on a printed adherend is frequently a lower bound on the adhesive and an upper bound on the adherend. **The failure locus is the result; the strength is a by-product.**

The adherend arrives at the bond line in a state set by post-cure, oxygen inhibition, wash chemistry and layer geometry. Post-cure alone changes modulus by 88 % on average and strength by 89 % [21]; wash agent changes flexural strength, conversion and residual monomer [15]; layer thickness significantly affects bond strength [18].

Mechanical abrasion is the only surface preparation with durable support after ageing [14,16,19]. Plasma helps immediately and does not survive ageing alone [13].

The evidence base is nine studies on the meta-analytic count [19], and none of them is an engineering lap-shear test of a vat-photopolymer-to-vat-photopolymer joint.

Dental shear-bond-strength values and lap-shear values are not comparable and must not be pooled.

Light-cured bond lines make optical access a joint design variable; the verified engineering response is to bond through a transmitting counterface [10].

The dissolution-and-interdiffusion mechanism of thermoplastic solvent welding cannot be presumed to transfer to a crosslinked photopolymer network, and this review located no primary evidence validating solvent welding as a structural joining route for one. No wider impossibility is claimed.

The durability evidence located covers only dental water thermocycling. Any other service environment requires locally generated evidence.

Research priorities, in order of value

One engineering lap-shear study of a vat-photopolymer-to-vat-photopolymer joint to ASTM D3163 or ISO 4587, with ISO 10365 failure-mode designation on every specimen. The central absence.

Bond strength as a function of oxygen-inhibited-layer removal: bonded as-printed, wiped, abraded, and post-cured-then-abraded.

Bond strength as a function of wash agent and duration, using the substrate-state variables already characterised in [15].

Post-cure state versus joint strength and failure locus, to test the §3 hypothesis.

Build orientation versus joint strength on a vat-photopolymer adherend, reported per ISO 17295:2023 orientation conventions [34].

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