

Low-Friction and Lubricious Surfaces on Printed Photopolymers: Additives, Grafts, Coatings, Migration and Wear

A state-resolved qualification framework from lubricating-function location to post-wear surface integrity

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ER-227 · Engineering Review · Version 0.4 · 19 September 2026

Abstract

Low friction on a printed photopolymer is not an intrinsic material property. It is the response of a complete tribosystem comprising the printed and post-cured resin, the location and attachment of the lubricating function, the counterface, contact geometry, load, speed, motion, temperature, environment and accumulated sliding history. Bulk solid lubricants, surface-segregated additives, covalently attached brushes, deposited coatings and hydrated layers can all reduce friction, but they replenish, migrate, wear and fail by different mechanisms.

This review defines a qualification architecture for low-friction and lubricious printed-photopolymer surfaces. It separates initial friction from durable lubricity; requires friction and wear to be paired with surface and counterface evidence; treats migration, blooming, leaching, transfer-film formation, coating loss and substrate exposure as time-dependent state changes; and preserves the distinction among dry, oil-lubricated and aqueous contacts. Direct evidence from photocurable vat-polymerisation composites is combined with bounded adjacent evidence from UV-cured coatings, grafted polymer brushes, hydrogel coatings and UV-cured thin films. The result is a non-compensatory framework for qualifying the intended tribosystem. No commercial formulation, universal additive loading, coating thickness, coefficient of friction, wear rate or service lifetime is established.

Keywords: printed photopolymer; lubricious surface; friction; wear; solid lubricant; polymer brush; hydrogel coating; migration; transfer film

1. Significance and scope

A low initial coefficient of friction can arise from a stable boundary layer, a transient contaminant, running-in debris, transfer-film formation, lubricant release or early destruction of a weak surface skin. These states are not equivalent. A surface can begin with low friction and then fail through depletion or delamination; it can begin with high friction and improve after a transfer film forms; or it can maintain a similar mean friction while wear damage and substrate exposure progress.

ER-227 addresses low-friction surfaces on already printed and post-processed photopolymers. Its central decision is whether the origin, location and persistence of the lubricating function are demonstrated under a declared tribosystem and whether the observed friction history remains compatible with acceptable wear and surface integrity.

1.1 Corpus boundary

ER-040 retains general tribosystem definition, friction and wear measurement, wear-rate calculation and transfer limits for printed parts. ER-086 retains analytical extractables and leachables study design and toxicological interpretation. ER-088 retains general topography, finishing and roughness metrology. ER-095 retains photoinitiator migration. ER-104 retains fluorinated photopolymer chemistry and PFAS boundaries. ER-168 retains general coating and encapsulation adhesion. ER-208 retains general surface-chemistry mapping. ER-225 retains plasma, corona and UV-ozone activation. ER-226 retains release layers used during manufacture. ER-228 retains antifouling and biofilm-resistance claims. ER-227 is restricted to creating and qualifying a lubricious service surface and to the migration, depletion, transfer and wear processes that change that state.

2. Apply the ER-040 tribosystem definition to the lubricious surface state

ER-040's complete tribosystem definition applies without modification. ER-227 adds three architecture-specific state variables: where the lubricating function resides, how that function is attached or retained, and how the modifier or layer was conditioned before contact. These variables must be recorded together with the ER-040 variables for the printed resin, counterface, geometry, load, motion, environment and accumulated contact history.

The direct vat-photopolymerisation evidence shows that filler identity and state, printability and cured composite structure remain linked for the formulation studied in [1]. The separate SLA-composite evidence links filler distribution and cured structure to friction and wear at publisher-abstract depth [7], but does not establish printability. Neither source makes results transferable between apparatuses or counterfaces. The material name alone cannot define the tribosystem.

3. Identify where the lubricating function resides

Four architectures require separate qualification:

- 1 a bulk modifier dispersed through the printed network;
- 2 an additive that segregates or blooms toward the surface;
- 3 a covalently or strongly anchored graft or brush; and
- 4 a deposited coating or hydrated layer supported by the printed substrate.

A bulk-filled part may replenish an exposed surface during wear, but filler agglomeration, optical attenuation and weak interfaces can also degrade printing or mechanics. A migrating additive may lower friction temporarily while changing composition with time or transferring to the counterface. A graft can be extremely thin and chemically anchored, yet incomplete coverage or bond scission may expose the substrate. A coating can separate surface and bulk functions, but introduces adhesion, cracking and delamination gates.

Direct photocurable-composite evidence supports treating solid-lubricant loading, cured structure, friction and wear as coupled variables [1,7]. In the boundary or brush-lubrication conditions reported for ultrathin oil-compatible coatings, grafting-to and grafting-from were equivalently effective when sufficiently viscous base lubricants were used [3]. The attachment route must still be declared as a reporting and reproducibility variable, but [3] does not establish it as the governing mechanism. UV-cured thin-film evidence shows that additives can alter the outer surface differently from the bulk [8]. These systems support architecture-specific questions, not a common recipe.

4. Preserve the printed and post-cured substrate state

The substrate beneath a lubricious surface remains a cured photopolymer. Layer orientation, conversion, residual species, filler distribution, wash history, post-cure, moisture and ageing can affect hardness, roughness, compliance, adhesion and migration. A surface coating can mask some features without eliminating substrate deformation or crack propagation. A bulk additive can alter cure and network density before it affects friction.

Qualification therefore begins before the tribology test. Record resin batch, build orientation, layer thickness, support removal, wash, drying, post-cure spectrum and temperature, storage and any polishing or activation. Where a modifier was incorporated before printing, show that the printed and cured state remains fit for the intended geometry. A friction benefit cannot compensate for incomplete cure, unacceptable dimensional drift or loss of structural integrity.

5. Separate friction, wear and damage

Friction force describes resistance to motion under the chosen conditions. Wear describes material removal, displacement or damage. The two may correlate in a particular experiment but are not interchangeable. Low friction can coexist with progressive coating loss, and a stable mass may conceal local cracking or transfer.

General friction and wear measurement practice, including wear-rate calculation and transfer limits, remains under ER-040. For a lubricious architecture, add the evidence needed to distinguish depletion, coating or graft loss, exposure of bulk modifier, substrate exposure and transfer of the modifier to the counterface. The UV-cured graphite/PTFE coating study couples coating composition to friction and wear [2]. The direct SLA composite study likewise supports joint interpretation of frictional stability and wear [7]. Neither supplies a universal acceptance value.

6. Treat running-in and transfer films as state changes

Running-in can smooth asperities, remove a weak surface layer, expose dispersed lubricant or build a transfer film. A mean coefficient calculated across this transition can hide the mechanism. The same final friction can follow from controlled formation of a stable interphase or from progressive destruction.

ER-040 retains the general treatment of running-in and transfer-film measurement. ER-227 asks only what the transition means for the declared lubricious architecture. If a transfer film is proposed, establish whether it contains the modifier and whether its coverage persists. If wear exposes fresh bulk modifier, demonstrate that the new surface retains acceptable integrity and does not generate unacceptable debris. If a coating or graft is depleted, identify the onset of substrate exposure. The architecture-specific evidence is a time-aligned chain of lubricating-function location, retained attachment, surface composition and counterface state.

7. Distinguish dry, oil and hydration lubrication

Dry sliding, oil-compatible brushes and hydrated hydrogel layers are different tribological systems. An oil-compatible graft depends on the surrounding lubricant, polymer-solvent affinity and the contact regime [3]. A hydrated layer depends on water retention, network structure and the ability of the layer and substrate to support load without collapse or dehydration [5,6]. Neither result transfers to dry service.

The hierarchical hydrogel study separates a water-rich lubricating surface from a tougher load-bearing core and evaluates repeated sliding [5]. The UV-induced polydopamine/hydrogel study addresses anchoring and wear on a non-photopolymer substrate [6]. These adjacent studies support a two-layer qualification question: does the outer layer maintain lubrication, and does the underlying structure support load and remain attached? Their chemistry, numerical performance and biological context are not design values for a printed resin.

8. Map migration, blooming, leaching and depletion

A surface-active additive may enrich the interface during cure, diffuse during storage, bloom after printing, leach into a liquid or transfer during sliding. These processes can improve initial friction while destabilising composition or exposure. Conversely, depletion may reveal a higher-friction substrate.

Bulk formulation and outermost-surface composition should therefore be measured separately and at defined times. The UV-cured thin-film AFM study demonstrates that additive-containing films can present altered surface adhesion and distribution relative to the underlying film [8]. It supports measurement of surface enrichment, not a conclusion about lubricity by itself. For liquid-contact

applications, chemical release and safety interpretation remain under ER-086. Low friction, low wear or absence of visible bloom does not establish acceptable migration.

9. Qualify coating and graft attachment after wear

An intact lubricious layer before testing does not prove retention after cyclic contact. Examine thickness or coverage where feasible, adhesion to the printed substrate, crack initiation, edge lifting, local delamination and substrate exposure. For grafted surfaces, use chemistry or another validated marker that distinguishes retained graft from bare substrate. For coatings, retain the general adhesion and barrier controls of ER-168 while adding tribological challenge.

Polymer-brush work on laser-textured substrates shows that texture, wetting and friction interact [4]. The hydrogel studies show why load support, hydration and anchoring must be considered together [5,6]. These sources do not establish that roughening is always beneficial. Texture may retain lubricant, disrupt brush coverage, concentrate stress or increase abrasion, depending on scale and counterface.

10. Control topography without reducing the problem to roughness

A single roughness value cannot describe orientation, feature spacing, peaks, valleys, waviness or layer-line direction. Nor does lower roughness guarantee lower friction. Printed surfaces are anisotropic and may evolve during wear. Record the measurement scale and direction, and relate topography to the actual motion path and counterface.

Where a lubricious coating levels a printed surface, distinguish geometric smoothing from chemical lubrication. Where texture is intentional, test whether it remains filled or covered after cycling. ER-088 retains general topography methodology; ER-227 uses only the measurements needed to interpret the lubricious state.

11. Requalify after environmental and processing challenges

Cleaning, sterilisation, solvent exposure, humidity, immersion, temperature cycling and storage can change additive distribution, coating adhesion, graft conformation and hydration. ER-042 retains sterilisation-method qualification for vat-printed photopolymers; ER-227 treats sterilisation only as a declared durability challenge to the lubricious state. A service-relevant challenge should be applied before repeating friction, wear and surface-state measurements. The challenge and the tribology test are separate operations and both require full conditions.

For aqueous systems, control fluid composition, temperature, replenishment and conditioning time. For oil systems, control lubricant identity, viscosity state and contamination. For dry systems, control humidity and debris removal. A result in one environment cannot be described as a general material property.

12. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Printed substrate	Resin, orientation, wash, post-cure, storage and initial surface	Treating all printed photoresins as one substrate
Lubricating architecture	Bulk additive, surface segregation, graft, coating or hydrated layer, with location and attachment	Calling every modifier “self-lubricating”
Declared tribosystem	Counterface, geometry, load, motion, speed, environment and duration	Reporting a context-free coefficient of friction
Time-resolved response	Friction trace, running-in, wear and transfer-film evidence	Equating low initial friction with durability
Retained surface state	Post-wear composition, coverage, cracking, delamination and substrate exposure	Accepting an intact pre-test coating as lifetime evidence
Migration and exposure	Time-dependent surface/bulk composition and, where relevant, measured release	Inferring safety from friction or mass loss

The gates are independent. A low friction value cannot compensate for an undefined counterface, unacceptable wear, coating loss or unmeasured migration.

13. Minimum reporting set

Report resin or formulation family; print orientation and exposed face; wash, drying and post-cure; storage and initial conditioning; modifier identity and whether it is bulk, surface-segregated, grafted or coated; concentration only as a formulation-specific experimental variable; graft or coating preparation and cure; thickness, coverage and attachment evidence; initial chemistry and topography; counterface identity, finish and geometry; load or pressure basis; motion, speed, stroke, frequency and duration; temperature, humidity and lubricant or fluid identity; friction trace and averaging rule; wear measurement and uncertainty; debris and transfer-film observations; post-wear chemistry, topography and failure state; cleaning, ageing or sterilisation challenge; and replicates.

Every numerical result must retain the complete tribosystem and surface state. No additive loading, graft density, coating thickness, coefficient of friction, wear rate or cycle count becomes a transferable target when those qualifiers change.

14. Knowledge boundary

ER-040 retains tribosystem definition, general friction and wear measurement, wear-rate calculation and transfer limits. Within that boundary, the evidence supports coupling formulation, printability and tribology for the direct photocurable formulation in [1] and coupling cured composite state with friction and wear in [7]; distinguishing UV-cured coatings from bulk-filled parts [2]; reporting graft route while recognising that [3] found grafting-to and grafting-from equivalently effective under its stated boundary conditions and identified sufficiently viscous base lubricant as the governing condition; measuring the interaction of texture, brush coverage and wetting [4]; separating hydration lubrication from load support and coating attachment [5,6]; and measuring additive-driven surface enrichment rather than assuming bulk-surface equivalence [8]. Most coating, graft and hydrogel evidence is mechanistically adjacent. It supports the qualification architecture but does not transfer chemistry, performance or lifetime to printed photopolymers.

15. Limitations

Only two source families directly concern photocurable printed composites [1,7]. The remaining studies concern UV-cured coatings, grafted brushes, hydrogel coatings or thin films on other substrates. Three sources were available only at publisher-abstract depth in the frozen preflight: [3], [6] and [7]. They support only bibliographic identity and their abstract-visible high-level experimental relation. No common resin, printer, post-cure, counterface, load, motion, environment or wear method spans the corpus. No source establishes safe migration, biocompatibility or a service-life acceleration factor for a printed photopolymer. The review supplies no commercial recipe or universal target.

16. Conclusions

Lubricity on a printed photopolymer must be qualified as a changing surface state within a complete tribosystem. The lubricating function may reside in the bulk, at a segregated surface, in a graft, in a deposited coating or in a hydrated layer; each architecture has distinct replenishment and failure modes. Initial friction is insufficient. The friction history must be paired with wear, counterface transfer and post-wear surface evidence. Dry, oil and aqueous contacts are not interchangeable, and migration or leaching requires separate chemical and safety assessment. A defensible claim is limited to the declared resin, post-cure, surface architecture, counterface, environment and accumulated sliding history.

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