

Surface Topography and Finishing of Vat-Printed Photopolymers: Roughness Metrology, Orientation, Stair-Stepping, Polishing and Functional Transfer

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Statement of Significance

Surface quality in vat photopolymerisation cannot be reduced to a single roughness number. A measured profile or areal texture is the result of the digital geometry, layer and pixel discretisation, optical point-spread behaviour, resin photochemistry, build orientation, support/contact state, washing, post-curing and any subsequent abrasive, polishing or smoothing operation. The same topography can be acceptable for one function and unacceptable for another: optical transmission, waveguide loss, appearance, metal contact, microbial attachment, sealing and tribological contact interrogate different scales and surface descriptors. This review separates surface formation, surface measurement and functional qualification so that roughness values are not transferred between instruments, orientations, post-processing states or applications without evidence.

Keywords: vat photopolymerisation; surface topography; surface roughness; Ra; Rz; Sa; stair-stepping; polishing; smoothing; SLA; DLP; LCD; profilometry

Abstract

Vat-photopolymerised parts are often described as having smooth or high-quality surfaces, yet published studies show that the realised topography depends on both process physics and measurement method. DLP formulation can change feature size and stair-stepping; LCD projection discontinuities can generate lateral texture; build direction alters roughness; post-curing and polishing change the measured surface state; and finishing can simultaneously change roughness, gloss and other functional outputs. This Engineering Review develops a state-based qualification framework for surface topography of SLA, DLP and LCD/MSLA photopolymers. It distinguishes profile from areal parameters, separates form/waviness/texture scales, requires explicit filter and instrument reporting, and treats orientation and surface identity as experimental variables rather than nuisance metadata. Polishing and chemical or abrasive smoothing are treated as manufacturing operations that create a new surface state, not as universal corrections. 3Dresyns Cleaning Paste CP1 Bio, Cleaning Paste CA1 Bio, Cleaning Fluid WS1 and ophthalmic material collections are included only as manufacturer implementation examples. Their commercial descriptions do not establish a universal roughness reduction or functional surface specification.

1. Scope and boundaries

ER-88 addresses the topography of cured vat-printed photopolymer surfaces and the controlled operations used to modify that topography after printing. It covers as-printed texture, vertical and lateral stair-stepping, orientation, pixel/layer discretisation, surface roughness measurement, polishing, abrasion and smoothing, together with transfer of the measured surface state to application-specific performance.

The paper is deliberately separated from neighbouring reviews. ER-10 addresses dimensional metrology and geometric fidelity across whole features and parts; ER-34 addresses separation/peel mechanics at the vat interface; ER-40 addresses tribological wear; ER-55 addresses optical waveguide propagation; ER-78 addresses colour and appearance metrology; ER-79 addresses metallization, where surface state is an activation variable. ER-88 is restricted to the surface-texture measurement chain and to how printing and finishing create the surface that those other functions may subsequently interrogate.

2. Surface topography is a multiscale state

A printed surface contains structure across multiple spatial scales. Part form and low-frequency waviness can coexist with layer stair-steps, pixel-edge structure, support scars, cured-resin menisci, local pores or debris, and much finer asperities. A single arithmetic mean roughness value cannot identify which physical scale created a deviation. It is therefore essential to distinguish the unfiltered measured surface from the filtered profile or areal texture used for a reported parameter.

Current ISO surface-texture standards provide separate frameworks for profile and areal evaluation. ISO 21920-2:2021 specifies terms, definitions and profile parameters [S1], while ISO 21920-3:2021 defines the profile specification operator [S2]. ISO 25178-2:2021 defines areal surface-texture parameters [S3]. These standards do not make a VPP part automatically comparable: the instrument, measurement area or trace, filter/nesting settings, direction, sampling and surface state still have to be declared.

Table 1. Surface quantities that should not be conflated

Quantity / state	What it can describe	What it does not establish
Profile roughness (e.g. Ra, Rz family)	Texture along a specified trace after the declared profile operations.	Areal isotropy, full-surface defect population or application performance.
Areal texture (e.g. Sa and related parameters)	Three-dimensional height distribution over a defined measured area.	Automatic equivalence to a profile metric or another instrument/filter.
Stair-stepping amplitude/periodicity	Layer- or pixel-linked deterministic surface structure.	Random micro-roughness or functional consequence by itself.
Gloss / optical scatter	Optical response of the finished surface under a defined geometry.	Direct surface height or a unique roughness value.
Support/contact scar state	Local damage or texture created by supports, platform/contact or removal.	The free-surface state elsewhere on the same part.
Polished/smoothed state	A new manufactured surface after material removal, redistribution or coating.	Properties of the original as-printed surface.

3. Printing creates deterministic and stochastic texture

VPP surface formation contains deterministic components imposed by digital discretisation and stochastic components imposed by the physical process. Kowsari et al. showed that photopolymer formulation can affect feature size, surface roughness and stair-stepping in DLP printing [1]. Shan et al. isolated a lateral stair-stepping mechanism in LCD VPP associated with the disconnected projected pixel pattern and demonstrated that deliberately defocusing the image reduced the measured roughness in their system [2]. These results are evidence that surface texture is not solely a CAD or layer-height problem: optics and resin response interact.

The practical implication is that nominal pixel size or layer thickness cannot be converted directly into an expected Ra or Sa. Overcure, optical blur, absorber content, local curvature and resin flow can attenuate or amplify digitally imposed edges. Conversely, a visually smooth surface can contain periodic structure that becomes important at a smaller measurement scale.

4. Orientation and surface identity must be explicit

Build orientation changes which physical mechanism forms a surface. Up-facing, down-facing, vertical and inclined walls may experience different projection, recoating, support and drainage histories. Poyraz found a significant build-direction effect on the roughness of photopolymerisation-printed hard resin specimens, with vertical and horizontal states not interchangeable [4]. Khodaii and Rahimi likewise treated surface angle as a controllable variable in stereolithographic roughness [3].

Reporting only a specimen orientation is still insufficient when a part contains several functional surfaces. A sealing face, an optical face, an electrode contact and a support-facing surface can occupy different orientations and post-processing histories on the same component. Qualification should therefore assign a stable surface identifier and record the local normal/build relationship for each measured region.

5. Measurement method can change the answer

Contact stylus profilometry, optical interferometry, confocal microscopy and other areal optical methods do not interrogate the same surface in the same way. Tip radius, lateral sampling, vertical range, reflectivity/transparency, thresholding, stitching and filter choices can alter the reported texture. Transparent or semi-transparent photopolymers are especially vulnerable to optical artefacts when subsurface scattering or reflections contaminate the height reconstruction.

The minimum defensible record therefore includes instrument principle, objective or stylus geometry where applicable, trace length or areal field, sampling spacing, evaluation direction, filters/nesting indices, excluded defects and replicate strategy. Raw topography retention is strongly preferred when a numerical claim will be compared across processes or over ageing.

Table 2. Minimum measurement record for a VPP surface-texture result

Field	Minimum record	Reason
Printed state	Printer/process, resin, layer thickness, exposure state, build orientation, surface identity.	Defines how the surface was created.
Post-processing	Wash, dry, post-cure, support removal, sanding/polishing/smoothing sequence.	Defines the actual surface measured.
Instrument	Measurement principle, instrument/model and probe/objective information.	Controls spatial response and artefacts.
Sampling	Trace/area dimensions, lateral spacing, measurement direction and number of locations.	Controls captured scales and anisotropy.
Processing	Form removal, filters/nesting indices, outlier/defect handling and parameter standard.	Makes the numerical parameter reproducible.
Uncertainty / replication	Replicates, location-to-location scatter and uncertainty where available.	Prevents one local trace from becoming a whole-part claim.
Functional link	Separate application-specific endpoint measured on the same declared surface state.	Prevents roughness from being treated as performance itself.

6. Polishing and smoothing create a new material surface state

Finishing is often described as though it simply removes printing artefacts. In reality, abrasion and polishing can remove the oxygen-affected outer layer, expose filler, round edges, alter dimensions, change gloss, modify wettability and generate residual scratches. Solvent or chemical smoothing can redistribute or extract surface material and may change local conversion or swelling. Each treatment therefore creates a new surface that requires its own measurement and, when relevant, functional retest.

Published dental-resin studies illustrate the point without establishing a universal polishing recipe. Wadhvani et al. measured stereolithographic and DLP temporary-resin surfaces before and after a defined polishing sequence and reported a significant change in roughness depth [5]. Büyükpolat et al. later showed material- and system-dependent changes in roughness and gloss after one-, two- and multi-step polishing systems, with additional polishing paste further changing the measured surface in their tested materials [7]. These findings cannot be transferred as a fixed reduction factor to unrelated engineering photopolymers.

7. Roughness is not a universal functional acceptance criterion

A surface-texture parameter becomes useful only when its relationship to the intended function has been established. Santos et al. combined roughness measurements with microbiological analysis for a specific VPP dental resin and demonstrated that surface and biological endpoints must be considered together rather than assuming a universal roughness threshold [6]. In optical and microfluidic contexts, Kowsari et al. and Shan et al. explicitly linked smoother printing strategies to applications such as micro-optics and microfluidic structures, but their process-specific findings do not create a cross-platform surface specification [1,2].

The same logic applies to contact resistance, sealing, tribology and metallization. Roughness can influence real contact area, fluid leakage, friction or coating nucleation, yet the sign and magnitude of the effect depend on material, scale and geometry. ER-88 therefore treats roughness as a measurable surface descriptor that may enter a qualification model, not as a surrogate for performance.

8. As-printed and finished surfaces require separate claims

A product or process may reasonably claim an as-printed texture, a finished texture, or a functional result after a defined finishing route, but those are different claims. The surface state should be frozen before testing: as-printed and washed; washed plus post-cured; support-removed; mechanically polished; chemically smoothed; coated; or aged. Combining data from those states in a single mean obscures the manufacturing route.

Golhin et al. reviewed surface roughness across polymer AM and emphasized the dependence of roughness on process and processing parameters [8]. For VPP qualification, that dependence should be converted into a controlled state tree rather than a catalogue of generic roughness ranges.

9. A state-chain model for VPP surface qualification

Table 3. Surface qualification chain

State	Question	Minimum evidence
Digital target	What local surface orientation and curvature are intended?	CAD surface identity; orientation; feature scale.
Projected/layered process	What discretisation and optical exposure create the surface?	Layer/pixel/projection state; exposure and resin condition.
As-printed green surface	What defects and deterministic texture exist before cleaning?	Representative microscopy/topography when accessible.
Washed/post-cured surface	How do cleaning and cure change the surface?	Controlled processing record + repeat topography.
Finished surface	What abrasion/polish/smoothing/coating operation was applied?	Full finishing sequence + material removal/dimensional check where relevant.
Functional surface	Does the declared surface state meet its application endpoint?	Application-specific test on the same state, orientation and region.

State	Question	Minimum evidence
Aged/reprocessed surface	Is the surface retained after realistic duty?	Repeat texture plus functional retest after defined exposure.

10. 3Dresyns implementation boundary

Controlled 3Dresyns documentation provides several implementation examples relevant to surface finishing. Cleaning Paste CP1 Bio is positioned as a cleaning and polishing paste for compatible printed resin and plastic surfaces [M1]; Cleaning Paste CA1 Bio is an abrasive cleaning paste [M2]; and Cleaning Fluid WS1 is documented for cleaning and surface smoothing of water-soluble and non-water-soluble 3D prints [M3]. The ophthalmic-lens collection also explicitly states that optical quality depends on print resolution, orientation, polishing and post-processing, not on resin selection alone [M4].

These are manufacturer-controlled process/product descriptions, not independent demonstrations of a universal Ra/Sa reduction, gloss gain, optical improvement or biological benefit. For ER-88 they establish that controlled finishing is an actual 3Dresyns workflow variable. Any quantitative performance statement still requires a defined base resin, geometry, processing route, measurement method and replicate result.

11. Minimum qualification protocol

- Define the functional surface(s) on the CAD model and assign stable identifiers before printing.
- Record build orientation and whether each measured region is up-facing, down-facing, vertical/inclined, support-facing or free.
- Freeze the resin, printer, layer, exposure, wash, dry and post-cure states before comparing surfaces.
- Measure at least one parameter set appropriate to the required scale; do not substitute Ra for Sa or vice versa without justification.
- Record instrument principle, sampling geometry, direction, filtering/nesting settings and replicate locations.
- Inspect deterministic texture such as layer/pixel stair-stepping separately from random micro-roughness where it matters.
- For polishing or smoothing, record every operation, abrasive/medium, duration, tool/contact condition and sequence.
- Check geometry or thickness after aggressive finishing when dimensional fidelity is important.
- Test the application-specific functional endpoint on the same declared finished surface state.
- Repeat both topography and function after ageing when service exposure can change the surface.

12. Failure-mode and discrimination matrix

Table 4. Common surface-quality failures and discriminating evidence

Observation	Competing explanations	Discriminating evidence
High Ra on one face only	Orientation; support scars; layer staircase; measurement direction.	Same-part multi-face map + orientation record + areal image.
Periodic ridges	Layer stepping; pixel grid; projection aliasing; recoating artefact.	Spatial-frequency/period check against layer and pixel geometry.
Optical haze despite low Ra	Subsurface scatter; microvoids; chemistry; fine-scale texture below instrument response.	Transmission/haze + microscopy/topography using an appropriate scale.
Polishing improves gloss but not function	Wrong roughness scale; contamination; exposed filler; unchanged geometry.	Topography + chemistry/cleanliness + application-specific endpoint.
Large scatter among replicate traces	Surface anisotropy; local defects; insufficient trace/area; support/contact heterogeneity.	Areal map, more locations and explicit region classification.

Observation	Competing explanations	Discriminating evidence
Chemical smoothing rounds features	Material dissolution/swelling rather than selective asperity removal.	Pre/post dimensional metrology + mass/thickness + surface topography.
Roughness changes after post-cure	Shrinkage, stress, surface conversion or contamination history.	Matched pre/post locations + cure record + conversion/state evidence where needed.
Good coupon surface, poor part surface	Different orientation, curvature, drainage, supports or local exposure.	Geometry-matched qualification specimen or direct part-surface measurement.

13. Research and standardisation priorities

- VPP round-robin studies using current ISO 21920/25178 vocabulary with shared raw topography datasets;
- cross-instrument comparison of contact and optical surface metrology on transparent and translucent photopolymers;
- spatial-frequency methods that separate layer, pixel and random roughness components rather than collapsing them into one Ra;
- geometry-aware surface maps for curved, microfluidic and optical components;
- paired topography and dimensional-loss measurements for mechanical polishing and chemical smoothing;
- functional transfer studies linking declared surface scales to optical loss, sealing, electrical contact, microbial attachment and coating adhesion;
- ageing studies that remeasure the same surface regions after water, solvent, UV, thermal or mechanical exposure;
- minimum reporting rules for support scars and local repair rather than excluding them without declaration.

14. Conclusions

Surface roughness in VPP is not an intrinsic scalar property of a resin. It is an output of the printer-light-material-geometry-post-processing chain and of the measurement operator used to interrogate the resulting surface. Layer and pixel discretisation, optical blur, resin response, orientation, support/contact state and finishing can all contribute at different spatial scales.

The strongest qualification approach is therefore state-based. Define the functional surface, record how it was printed, preserve the measurement operator, distinguish profile from areal texture, document polishing or smoothing as a manufacturing step, and test the downstream function on the same surface state. This prevents visually persuasive but scientifically weak claims such as “ultra-smooth” from being transferred across materials, orientations or instruments without evidence.

For 3Dresyns, existing polishing, abrasive-cleaning and surface-smoothing products provide implementation routes, while optical product collections already recognise surface finish as a system variable. ER-88 converts that implementation reality into an evidence architecture: manufacturer processing options can define what to test, but only controlled topography and function measurements establish the result.

Limitations

The independent literature combines engineering, optical and dental VPP studies whose resins, printers, geometries and roughness methods are not interchangeable. Numerical roughness values are therefore not pooled. The review does not prescribe a universal polishing sequence or an application-independent roughness threshold. Some functional examples are used only to demonstrate transfer limits and remain governed by their dedicated ER papers.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, surface-metrology and finishing qualification framework, writing and critical review.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. Manufacturer documentation is included only as implementation context and is separated from independent scientific evidence.

Data availability

No new experimental dataset was generated for this review. Scientific statements derive from the cited literature and standards; manufacturer examples derive from controlled 3Dresyns documentation.

Company information

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