

Color and Appearance Metrology in Vat-Printed Photopolymers: CIELAB, CIEDE2000, Metamerism, Gloss, Surface Texture and Gonioappearance

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Statement of Significance

A color name, a nominal RAL/NCS target or a single ΔE value is not a complete appearance specification for a vat-printed photopolymer. Measured color depends on illuminant, observer, instrument geometry, background, thickness, translucency, surface texture, gloss and specimen orientation. Printing and post-processing can change several of these variables without changing the nominal pigment recipe. Metallic, fluorescent and highly translucent materials add further measurement constraints. This review separates color coordinates from color difference, appearance from spectral reflectance, and formulation color from finished-part color, and proposes a qualification architecture for reproducible color and appearance claims in SLA, DLP and LCD/MSLA photopolymer systems.

Keywords: colorimetry; CIELAB; CIEDE2000; metamerism; gloss; surface texture; translucency; gonioappearance; vat photopolymerisation; SLA; DLP; color matching; RAL; NCS

Abstract

Color and appearance in vat photopolymerisation are coupled material-process-surface properties. CIELAB coordinates describe a color stimulus under declared measurement conditions, while CIEDE2000 provides a defined color-difference calculation from CIELAB coordinates. Neither quantity is independent of illuminant, observer, measurement geometry, background or specimen state. Additive-manufacturing studies show that printing orientation, layer thickness, post-curing, polishing, glazing, ageing media and surface roughness can alter measured color and translucency. Independent work on 3D-printed polymers also demonstrates that gloss and roughness change with surface finishing, making visual match a broader problem than chromatic coordinates alone. This Engineering Review defines minimum controls for color matching, batch comparison, post-process drift and appearance qualification in vat-printed photopolymers. It distinguishes ordinary diffuse/opaque specimens from translucent, fluorescent and gonioapparent metallic systems, for which single-geometry color data can be incomplete. 3Dresyns Custom RAL/NCS Colours, Basic Color Pastes, Special Metallic Colors and 3D-ADD MATT1 are included only as manufacturer implementation examples; no universal ΔE tolerance, gloss target or cross-printer color equivalence is inferred from product positioning.

1. Scope and boundaries

ER-78 addresses measurement and qualification of the visual appearance of finished vat-printed photopolymer parts. The primary questions are: what was measured; under what optical geometry and illumination; on what specimen state; against which reference; and whether the reported metric is sufficient for the appearance claim being made. It covers CIELAB coordinates, CIEDE2000 color differences, metamerism risk, background and thickness effects, translucency/opacity as contextual variables, gloss, surface texture and gonioappearance.

The paper does not replace ER-44, which addresses photoabsorbing fillers, optical response and cure-depth control. A pigment can change both appearance and curing, but ER-78 begins at the measurement of the resulting part appearance. ER-72 owns environmental-ageing mechanisms and property retention; ER-78 uses before/after color data only as an appearance measurement example. ER-55 owns waveguide/light-guide propagation, and ER-56 owns fluorescence/phosphorescence photophysics. Fluorescent samples are mentioned here only to establish why conventional reflectance-color measurements may require additional spectral controls. ER-88 owns surface-texture metrology and finishing operations. ER-78 uses roughness and gloss only as appearance variables measured on the declared finished surface state.

2. Color coordinates and color differences answer different questions

ISO/CIE 11664-4:2019 defines the CIE 1976 $L^*a^*b^*$ color space for specified tristimulus values, including lightness, chroma and hue correlates [S1]. A set of L^* , a^* and b^* coordinates describes a measured color stimulus under declared conditions. It does not by itself state whether two samples are acceptably matched.

ISO/CIE 11664-6:2022 specifies the CIEDE2000 color-difference calculation from CIELAB input values [S2]. A ΔE_{00} result is therefore a comparison metric, not a material constant. The reference, illuminant/observer, instrument geometry, specimen background, thickness and surface state remain part of the measurement. ASTM D2244 similarly warns that color differences and tolerances should be compared within the same color-scale system and that gloss and texture can affect commercial acceptability [S4].

Table 1. Appearance quantities that must not be conflated

Quantity	What it describes	Main controls
L^* , a^* , b^*	Coordinates of the measured color stimulus in CIELAB.	Illuminant, observer, geometry, calibration, background, thickness, specimen state.
ΔE_{00}	Magnitude of color difference calculated by CIEDE2000 between two declared CIELAB states.	Exact reference and same measurement conditions; report direction/components where useful.
Spectral reflectance / transmittance	Wavelength-resolved optical response underlying color and transparency.	Spectral range, bandwidth, geometry, integrating sphere/specular setting where applicable.
Gloss	Specular-reflection appearance at a defined geometry.	Measurement angle, surface flatness/texture, orientation and instrument aperture.
Surface roughness / texture	Geometric surface state that can redistribute reflected light and change apparent color/gloss.	Metric, cutoff/filter, scan area/direction, print orientation and post-processing.
Translucency / opacity descriptor	Influence of transmission and background on observed color.	Thickness, black/white or other backgrounds, geometry and spectral method.
Gonioappearance	Angle-dependent color/brightness, especially metallic or effect-pigment systems.	Illumination/viewing angles, flake orientation, gloss and texture; multiangle measurement.

3. Illuminant, observer and geometry are part of the result

A numerical color coordinate is meaningful only with the conditions that generated the tristimulus values. ISO/CIE 11664-2:2022 defines CIE standard illuminants including A, D65 and D50 [S3]. Changing the illuminant can change the relative weighting of a specimen reflectance spectrum and therefore the perceived or calculated match. This is the physical basis of metamerism: two samples can match under one illuminant while diverging under another because their spectral reflectance functions differ.

For production qualification, a target should therefore identify the illuminant, standard observer, instrumental geometry and treatment of the specular component. A nominal RAL or NCS designation is useful as a target identity, but the physical reference specimen or a controlled spectral reference and an agreed measurement method are needed if a numerical tolerance is to be enforced. ER-78 does not define a universal acceptable ΔE_{00} because acceptability depends on application, color region, viewing context, surface appearance and stakeholder agreement.

4. Printing parameters can become appearance variables

VPP creates a layered, anisotropic optical surface and a cure-state history. Lee et al. found that layer thickness and printing orientation significantly affected ΔE_{00} color-stability results for a tooth-colored 3D-printed resin during immersion ageing [2]. That study is material- and protocol-specific, but it demonstrates that print settings can change the measured appearance trajectory even when the nominal resin identity is unchanged.

A color qualification should therefore freeze printer, wavelength, exposure strategy, layer thickness, orientation, washing, drying and post-curing when the objective is lot-to-lot or formulation comparison. If the objective is cross-platform equivalence, those process variables should be deliberately varied and the finished-part appearance should be remeasured rather than inferred from the liquid color concentrate.

5. Post-processing and surface state can dominate the visual result

Scotti et al. measured color change, hardness and surface roughness in a 3D-printed composite resin before and after defined finishing/ageing states [1]. More recent work by Nowakowska-Toporowska et al. used spectrophotometry and CIEDE2000 to show that material, conditioning medium, time and surface treatment affected color change in three 3D-printed dental resins [4]. These studies do not establish universal thresholds for engineering resins, but they support a general control principle: the appearance specimen must represent the finished process state.

Žigon et al., working with FDM polymer substrates rather than VPP, measured color, gloss and roughness after sanding and coating and showed that these surface descriptors change together [5]. ER-78 uses this as transferable appearance-metrology evidence, not as proof of a VPP-specific magnitude. In vat-printed parts, polishing, glazing, solvent smoothing, support removal and surface residue can similarly change the specular/diffuse balance; those effects must be measured on the actual process route.

6. Gloss and color should be reported separately

ISO 2813:2014 specifies gloss measurement at 20°, 60° and 85° for non-textured coatings on plane opaque substrates [S5]. Its scope limitation is important for VPP: many printed parts are curved, textured, translucent or anisotropic, so direct use of an ISO 2813 value may require a dedicated planar witness coupon rather than measurement on the functional geometry.

A matte additive can lower specular gloss while producing only a modest change in chromatic coordinates, and a polishing process can increase gloss while shifting measured L^* or chroma because surface scattering has changed. Consequently, a color-match claim and a gloss-match claim should use separate acceptance variables. For scanning applications, low gloss may improve image acquisition, but ER-78 does not infer scanner accuracy from gloss alone; that performance requires scanner-specific validation.

7. Background, thickness and translucency

The scoping review by Espinar et al. found that color and optical properties of 3D-printed restorative polymers were incompletely reported and specifically noted the influence of background on color measurement [3]. For translucent specimens, color coordinates can therefore change with substrate/background and thickness even without any chemical change. A thin printed wall measured over black can produce a different result from the same material over white or from a thick, effectively opaque specimen.

Minimum reporting should include specimen thickness and the measurement background whenever transmission is non-negligible. If translucency or opacity is itself a target, the exact calculation and black/white or other backing conditions must be stated. ER-78 deliberately avoids treating a translucency parameter from one dental protocol as a universal optical constant for every VPP resin.

8. Metamerism cannot be diagnosed by one daylight ΔE value

Two color recipes may reach a small ΔE_{00} under D65 yet have different spectral reflectance curves. Under another illuminant, their relative tristimulus values can change and the match can deteriorate. This is particularly relevant when a custom color is made with different pigment/dye packages, when a printed polymer is compared with a painted metal or molded plastic master, or when photoinitiator/absorber changes alter the short-wavelength reflectance.

A metamerism-sensitive qualification should retain spectral data and evaluate the match under at least the illuminants relevant to the intended use. Visual assessment under controlled lighting remains a useful complement to instrumental data when the end point is human appearance. A single RGB photograph or screen rendering is not a substitute for a controlled colorimetric measurement.

9. Metallic and gonioapparent colors require an additional branch

Metallic-flake systems are angle dependent because illumination/viewing geometry and flake orientation affect the reflected intensity and color. ASTM E2194 is specifically designed for multiangle color measurement of metal-flake pigmented materials and states that even specimens with the same multiangle color values can fail visual match when gloss, orange peel, texture or flake orientation differ [S6].

This matters directly to layerwise manufacturing: particle orientation, sedimentation, recoating, cure shrinkage and surface finishing may change flake presentation. ER-78 therefore does not treat a single CIELAB/ ΔE_{00} value at one geometry as sufficient qualification for a metallic 3D-printed appearance. The measurement method should be selected according to whether the material is ordinary diffuse, translucent, fluorescent or gonioapparent.

10. Fluorescent materials are a scope boundary, not ordinary reflectance colors

A fluorescent material adds emitted light to reflected light under excitation. The measured apparent color can therefore depend strongly on the spectral power distribution and UV content of the illuminant. ER-56 addresses fluorescence/phosphorescence excitation-emission, quantum yield and lifetime questions. ER-78 requires only that a color-control plan identify fluorescent specimens and avoid assuming that an ordinary non-fluorescent reflectance protocol is automatically sufficient.

11. Qualification architecture

Table 2. Minimum qualification architecture for color and appearance

Layer	Minimum record	Failure prevented
Reference	Physical master or controlled spectral reference; target identity/version.	Comparing against an ambiguous screen image, catalogue name or aged master.
Specimen state	Resin lot/version, printer, layer/orientation, wash, post-cure, finishing, conditioning.	Attributing process-state variation to colorant formulation.
Colorimetry	Instrument, geometry, calibration, illuminant, observer, specular setting, $L^*a^*b^*$ and ΔE_{00} .	Non-comparable color numbers.
Background / thickness	Backing color/spectrum and specimen thickness for non-opaque samples.	False differences caused by transmission/background.
Surface appearance	Gloss geometry and roughness/texture metric where relevant.	Calling chromatic match a complete visual match.
Metamerism	Spectral data and secondary illuminant(s) where cross-lighting match matters.	Daylight-only match that fails in service lighting.
Special appearance	Multiangle branch for metallic/gonioapparent; emission-aware branch for fluorescent samples.	Applying ordinary diffuse-color methods outside their useful scope.
Replicates / mapping	Replicate parts and spatial locations/orientations.	Missing within-part, between-part or build-direction variability.

12. 3Dresyns implementation boundary

The controlled August 2026 3Dresyns TDS system includes Custom RAL or NCS Colors, Basic Color Pastes and Special Metallic Colors, and separately includes 3D-ADD MATT1 as a matting additive [M1-M4]. These products provide real implementation cases for ordinary color matching, gonioapparent appearance and gloss control. Their catalogue presence is not independent evidence of a particular ΔE_{00} , metamerism index, gloss value or cross-printer reproducibility.

For Custom RAL/NCS work, the defensible deliverable is therefore an agreed reference plus a declared measurement protocol and tolerance on the finished printed state. For Basic Color Pastes, dosage alone should not be treated as a color coordinate because base resin, thickness, cure state and background remain influential. For Special Metallic Colors, multiangle/gonioappearance controls should be considered rather than ordinary single-angle color matching. For MATT1, a lower-gloss positioning should be validated by a declared gloss method on a suitable specimen; scanner performance is a separate application endpoint.

13. Minimum reporting checklist

- exact resin, colorant/additive identity or controlled formulation code and batch;
- printer/light-engine, wavelength, exposure strategy, layer thickness and build orientation;
- washing, drying, post-curing, polishing/glazing/smoothing and conditioning state;
- reference specimen or spectral target and its version/condition;

- instrument make/model or equivalent measurement capability, calibration and aperture;
- measurement geometry, specular component treatment, illuminant and standard observer;
- L^* , a^* , b^* values for reference and sample, not only scalar ΔE_{00} ;
- color-difference formula stated explicitly; use ΔE_{00} only with CIEDE2000-defined inputs;
- specimen thickness and backing/background for translucent or partially transmitting samples;
- gloss angle and geometry when gloss is a controlled appearance variable;
- surface roughness/texture metric and measurement direction/area when texture affects appearance;
- spectral comparison under additional illuminants where metamerism is relevant;
- multiangle method for metallic/gonioapparent materials where applicable;
- fluorescent/emissive classification and excitation-aware method where applicable;
- replicate count, measurement locations and uncertainty/within-build variation;
- predefined acceptance criteria appropriate to the application rather than an undocumented universal ΔE threshold.

14. Failure-mode and discrimination matrix

Table 3. Common appearance observations and discriminating evidence

Observation	Competing explanations	Discriminating evidence
ΔE_{00} changes after post-cure	Chemical conversion/yellowing; temperature history; surface gloss change.	Spectral reflectance + gloss + controlled before/after specimen state.
Good match on white, poor match on black	Translucency/thickness/background effect; different scattering.	Repeat on declared black/white backings + transmittance/opacity descriptor.
Good D65 match, poor warm-light match	Metamerism from different spectral reflectance curves.	Compare spectra and calculate/visually assess under relevant secondary illuminant.
Instrument match, visual mismatch	Gloss/texture/geometry; spatial non-uniformity; gonioappearance.	Gloss + roughness + multiangle/spatial mapping as appropriate.
Metallic part changes with orientation	Flake orientation; surface texture; anisotropic layer structure.	Multiangle color data + orientation-controlled specimens + microscopy/texture evidence.
Color drifts between printers	Exposure/cure state; layer/orientation; optical power/spectrum; post-process differences.	Frozen resin lot with cross-platform process-state and finished-part color measurements.
Matte part scans better	Reduced specular highlight; scanner algorithm/geometry; surface texture change.	Independent scanner accuracy/repeatability test plus measured gloss/texture.

15. Research and standardisation priorities

- VPP-specific round-robin colorimetry using common opaque and translucent reference geometries;
- systematic separation of pigment concentration, cure conversion, layer thickness, orientation and surface finish effects;
- metamerism datasets for printed polymer versus molded, painted or coated reference materials;
- multiangle appearance studies of metallic/effect-pigment VPP parts with controlled particle orientation and sedimentation;
- spatial color/gloss mapping across curved and large-area parts rather than single-point coupon measurements;
- paired gloss, roughness and color datasets after washing, polishing, glazing and solvent-smoothing workflows;
- methods for fluorescent VPP colors that combine reflectance and emission under declared excitation spectra;
- application-specific acceptance criteria tied to visual function rather than universalized ΔE thresholds.

16. Conclusions

Color in a vat-printed photopolymer is not defined completely by a pigment recipe or a scalar ΔE . CIELAB coordinates, CIEDE2000 color difference, spectral response, gloss, texture, translucency and viewing geometry describe different aspects of appearance and should be controlled according to the material class and intended use.

The evidence shows that printing orientation, layer thickness, finishing, post-processing and ageing can alter measured color or surface appearance in 3D-printed resins. These effects are not universal in magnitude, but they are sufficient to reject formulation-only color qualification. The finished printed and post-processed state must be the measurement state for a finished-part claim.

For 3Dresyns implementation, Custom RAL/NCS Colours, Basic Color Pastes, Special Metallic Colors and MATT1 create four distinct qualification problems: reference matching, ordinary pigment adjustment, gonioapparent measurement and gloss control. None should be assigned a universal tolerance from product positioning alone. A defensible claim requires a declared reference, instrument/geometry, illumination/observer, specimen state and application-specific acceptance criterion.

Limitations

Much of the direct VPP color literature is concentrated in dental restorative materials, where translucency, shade matching and clinical acceptability are unusually important. ER-78 uses those studies to establish measurement sensitivities, not to transfer dental perceptibility/acceptability thresholds to industrial, optical or aesthetic 3Dresyns applications. The surface-finishing study cited for combined color/gloss/roughness evidence used FDM substrates and is treated only as transferable appearance-metrology evidence. No new color measurements are reported in this review.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, color/appearance 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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