

Reproducibility limits of working-curve characterisation in vat photopolymerisation: a methodological perspective

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Keywords

vat photopolymerisation; working curve; Jacobs equation; depth of penetration; critical exposure; methodological synthesis; interlaboratory variability; spectral bandwidth; reproducibility; additive manufacturing; characterisation methodology

Abstract

The working-curve measurement, introduced by Jacobs in 1992, remains the foundational characterisation of resin behaviour in vat photopolymerisation additive manufacturing. The two fit parameters of the Jacobs model - the depth of light penetration D_p and the critical exposure for gelation E_c - are routinely reported on commercial datasheets and in the peer-reviewed literature. Recent interlaboratory studies coordinated by the National Institute of Standards and Technology indicate that these parameters are reported with substantial dispersion across laboratories examining the same resin: a 2024 study reported D_p varying by up to a factor of seven and E_c varying by up to a factor of seventy across twenty-four participating laboratories, and a follow-up study under controlled bandpass-filtered light sources reduced this dispersion substantially. A parallel publication extended the Jacobs model analytically to broadband sources, and separate single-laboratory studies in Progress in Additive Manufacturing report intensity-dependent working-curve fit parameters. These observations support the reading that D_p and E_c , as currently measured, are coupled to the spectral characteristics of the light source, the irradiance at which the measurement is performed and the procedural choices of the measuring laboratory, rather than behaving as material constants in the strict sense. This Perspective synthesises the published evidence on working-curve variability, enumerates the methodological dimensions implicated and discusses reporting considerations that the available data support. The synthesis is restricted to vat photopolymerisation processes that share the Jacobs framework and does not propose a new standard or protocol.

1. Introduction

The working-curve measurement is the foundational characterisation of resin behaviour in vat photopolymerisation. First demonstrated by Jacobs in 1992 [1], it relates the cured layer thickness to the applied radiant exposure through a semi-empirical relation, and the two fit parameters that result from this relation — the depth of light penetration D_p and the critical exposure for gelation E_c — are routinely reported on commercial datasheets and in the peer-reviewed literature on photopolymer additive manufacturing.

A recent interlaboratory study coordinated by the National Institute of Standards and Technology [4] documents substantial dispersion in these parameters when nominally identical measurements are performed across laboratories. Twenty-four participating laboratories measuring aliquots from a single batch of resin reported D_p values varying by up to a factor of seven and E_c values varying by up to a factor of seventy. A subsequent study from the same group [6], in which calibrated bandpass- filtered light sources were distributed to participating laboratories, reduced this dispersion substantially and produced aggregate values of $D_p = 39.2 \pm 3.7 \mu\text{m}$ and $E_c = 12.3 \pm 3.0 \text{ mJ/cm}^2$ at 385 nm, and $D_p = 69.3 \pm 3.8 \mu\text{m}$ and $E_c = 17.9 \pm 2.3 \text{ mJ/cm}^2$ at 405 nm.

These findings raise a methodological question that the vat photopolymerisation literature has not yet uniformly addressed: which components of the working-curve measurement chain account for the documented dispersion, and under what operational conditions do the reported D_p and E_c values apply. A parallel publication from the same group extends the Jacobs model analytically to broadband light sources [5], addressing one of these components and indicating that the apparent fit parameters obtained under polychromatic exposure depend on the spectrum of the light source used to perform the measurement.

This Perspective synthesises the published evidence on working- curve variability in vat photopolymerisation, enumerates the methodological dimensions implicated by the cited studies, and discusses reporting considerations that the available data support. The scope is restricted to vat photopolymerisation processes that share the Jacobs working-curve framework, namely stereolithography, digital light processing and liquid crystal display photopolymerisation. Two-photon polymerisation, volumetric additive manufacturing, jetting-based platforms and other photopolymer additive manufacturing modes are outside scope. The Perspective does not propose a new standard or protocol.

2. The Jacobs model and its assumptions

The semi-empirical model introduced by Jacobs [1] relates the cured layer thickness C_d in vat photopolymerisation to the applied radiant exposure E through

$$C_d = D_p \cdot \ln(E / E_c) \quad (1)$$

where D_p is the characteristic depth of light penetration in the resin, corresponding to attenuation of incident irradiance to $1/e$ under the Beer-Lambert description, and E_c is the critical radiant exposure associated with gelation. The slope of C_d plotted against $\ln(E)$ yields D_p , and the value of E at $C_d = 0$ yields E_c . These parameters are widely used to characterise resin behaviour and material-printer processing windows [1,2,4].

The standard Jacobs relation is commonly applied under assumptions that include a nominally monochromatic light source, reciprocity between exposure time and irradiance, and negligible photobleaching during the measurement [1,4]. These assumptions provide a useful simplified description, but they are not satisfied uniformly by current vat-photopolymerisation hardware and resin systems.

LED sources used in vat photopolymerisation have finite spectral bandwidth rather than perfectly monochromatic emission [3,5]. In the NIST interlaboratory study, spectra from five nominally "405 nm" DLP printers showed peak wavelengths from approximately 402 to 411 nm [4]. Because resin absorption varies with wavelength, such spectral differences can change the optical attenuation represented by the apparent Dp [4,5].

A recent extension of the Jacobs model addresses the monochromatic assumption explicitly. Caplins and colleagues [5] derive a polychromatic generalisation in which the contribution of each spectral component of a broadband source to the cure depth is integrated across the emission band weighted by the wavelength-dependent absorption of the resin. Their analysis indicates that the apparent Dp and Ec extracted from a working curve measurement under a broadband source depend not only on the resin chemistry and on the photoinitiator absorption profile, but also on the spectral width and centre wavelength of the light source used to perform the measurement.

The implication for interpretation is direct: under the Jacobs model in its original monochromatic form, Dp and Ec are read as material constants. Under the polychromatic extension, the apparent Dp and Ec obtained experimentally depend on both the resin chemistry and the optical delivery conditions under which the measurement is performed. The interpretation of Dp and Ec as material constants therefore depends on the modelling assumptions under which the working curve is analysed. The interlaboratory evidence discussed in the following section examines this distinction quantitatively.

3. Empirical evidence of measurement variability

Three peer-reviewed publications from the National Institute of Standards and Technology, together with separate academic contributions, document the quantitative dispersion of working-curve parameters when nominally comparable measurements are performed across laboratories or under different optical conditions.

Kolibaba and colleagues [4] coordinated an interlaboratory study in which twenty-four individual laboratories performed a working-curve measurement on aliquots from a single batch of vat photopolymerisation resin. The participating laboratories represented academic and industrial settings. Each laboratory measured cure depth as a function of radiant exposure under its own optical and procedural conditions, using its own thickness-measurement procedure, and reported Dp and Ec from fits to equation (1). The dispersion was substantial: Dp varied by as much as a factor of seven and Ec by as much as a factor of seventy. The authors attributed the scatter to the lack of a common procedure, variation in light engines, epistemic uncertainty associated with fitting the Jacobs equation over different cure-depth ranges, and thickness-measurement tools with insufficient precision for the regime studied.

Within the same study, spectral characterisation of five nominally "405 nm" printers showed nearly ten nanometres of variation in peak wavelength. Optical Dp values calculated from the resin absorbance spectrum at the corresponding source wavelengths differed substantially across this range. This analysis identifies source spectrum as one contributor to the observed dispersion, alongside procedural differences, thickness-measurement precision and fitting-related epistemic uncertainty documented in the interlaboratory study.

A follow-up interlaboratory study [6] performed working-curve measurements using calibrated, reproducible bandpass-filtered light sources at 385 nm and 405 nm distributed to participating laboratories. Under these spectrally controlled conditions, interlaboratory variability in Dp and Ec was reduced substantially relative to the first study. The aggregate values reported were $Dp = 39.2 \pm 3.7 \mu\text{m}$ and $Ec = 12.3 \pm 3.0 \text{ mJ/cm}^2$ at 385 nm, and $Dp = 69.3 \pm 3.8 \mu\text{m}$ and $Ec = 17.9 \pm 2.3 \text{ mJ/cm}^2$ at 405 nm. The contrast between the two studies supports a major contribution from source spectral characteristics to the observed interlaboratory dispersion. The first study nevertheless shows that procedure, exposure-range selection and thickness measurement also contribute, so the relative variance attributable to spectrum alone is not established [4,6].

A parallel publication by the same research group [5] extends the Jacobs model analytically to broadband light sources, as discussed in section 2. The extension predicts that the apparent Dp and Ec extracted from a working-curve measurement under a non-monochromatic source are joint functions of the resin absorption profile and the source emission spectrum. The interlaboratory observations in [4] and [6] are consistent with this analysis.

Separately from the NIST interlaboratory programme, two studies published in Progress in Additive Manufacturing report quantitative effects of light intensity on apparent working-curve fit parameters within single laboratories. Rudenko and colleagues [7] document that for a pigmented vat-photopolymerisation resin measured at 385 nm, Ec rises from 1.1 mJ/cm² to 4.24 mJ/cm² and cure depth rises from 43.7 μm to 70.2 μm as incident light intensity is increased from 1 mW/cm² to 15 mW/cm². For a transparent formulation, Ec rises from 1.94 mJ/cm² to 4.61 mJ/cm² across the same intensity range, with cure depth rising from 87.7 μm to 131.1 μm . Billerbeck and colleagues [8] report an analogous intensity dependence of working-curve fit parameters in a separate set of formulations.

Taken together, these studies indicate that reported Dp and Ec can depend on source spectrum, can vary with irradiance for at least some resin systems, and are sensitive to procedural choices in interlaboratory measurement [4-8]. The available evidence does not establish a universal hierarchy or variance decomposition among these factors.

4. Methodological dimensions implicated

The evidence in section 3 directly supports source spectrum, irradiance and procedural measurement choices as contributors to reported working-curve variability. Two additional measurement-science considerations are relevant to the same chain: radiometer spectral response and calibration [9,10], and post-exposure polymerisation of partially cured specimens [11,12]. The latter two are supported by radiometry and photopolymerisation literature but have not been quantitatively isolated as contributors in the interlaboratory working-curve studies. Figure 1 situates these factors within the measurement chain.

4.1 Spectral characterisation of the light source

The original Jacobs treatment assumes nominally monochromatic exposure [1,4]. LED sources used in current vat-photopolymerisation hardware have finite spectral bandwidth [3,5]. The polychromatic extension introduced by Caplins and colleagues [5] shows that the apparent Dp and Ec extracted from a broadband measurement depend on the source spectrum together with the wavelength-dependent absorption of the resin. In the NIST interlaboratory study, five nominally "405 nm" DLP printers showed peak wavelengths from approximately 402 to 411 nm [4]. The nominal wavelength alone therefore does not fully specify the optical delivery used for a working-curve measurement.

4.2 Radiometer calibration and irradiance traceability

The radiant exposure E in equation (1) is the time integral of irradiance. Accordingly, any bias in measured irradiance alters the exposure values assigned to the working-curve data. UV radiometer response is wavelength dependent, and calibration uncertainty depends on the relation between the instrument spectral response and the spectra of the calibration and test sources [9]. CIE 220:2016 provides characterisation and calibration methods for UV radiometers, including spectral-response considerations [10]. These sources establish spectral mismatch as a radiometric error mechanism, although its quantitative contribution to working-curve interlaboratory dispersion has not been isolated.

4.3 Light intensity and the assumption of intensity-independent D_p and E_c

Two separate studies in Progress in Additive Manufacturing [7,8] report that the working-curve fit parameters D_p and E_c depend on the incident light intensity at which the working curve is measured. Rudenko and colleagues [7] document E_c rising from 1.1 mJ/cm² to 4.24 mJ/cm² and cure depth rising from 43.7 μ m to 70.2 μ m for a pigmented vat-photopolymerisation resin at 385 nm, as light intensity is increased from 1 mW/cm² to 15 mW/cm². Billerbeck and colleagues [8] report analogous intensity-dependent behaviour in a separate set of formulations and laboratory setting. These observations indicate that the apparent D_p and E_c obtained experimentally may depend on irradiance conditions for at least some resin systems and measurement configurations, which is not captured by treating these parameters as material constants independent of the measuring source.

4.4 Post-print interval and dark polymerisation

Cure-depth measurement on a working-curve specimen is performed after illumination has ended. Independent photopolymerisation studies show that radical conversion can continue during this post-exposure interval. Farsiani and colleagues [11] quantified dark polymerisation after partial radical photocuring and found that its extent and kinetics depend on prior light intensity, exposure duration and material state. Aromaa and Vallittu [12] showed continued post-curing in a dimethacrylate system and found that oxygen exposure suppressed the post-illumination increase in conversion and was associated with lower surface microhardness. These studies do not quantify the contribution of handling interval to working-curve interlaboratory dispersion, but they establish a mechanism by which a partially cured film can evolve between exposure and thickness measurement.

4.5 Interaction among methodological dimensions

The factors in sections 4.1-4.4 act at different points in the same measurement chain. Source spectrum affects resin attenuation; radiometer response affects assigned irradiance and exposure; incident intensity can alter fitted working-curve parameters for some resin systems; and post-exposure polymerisation can alter the specimen before thickness measurement. The cited literature does not provide a formal variance decomposition of their joint contributions.

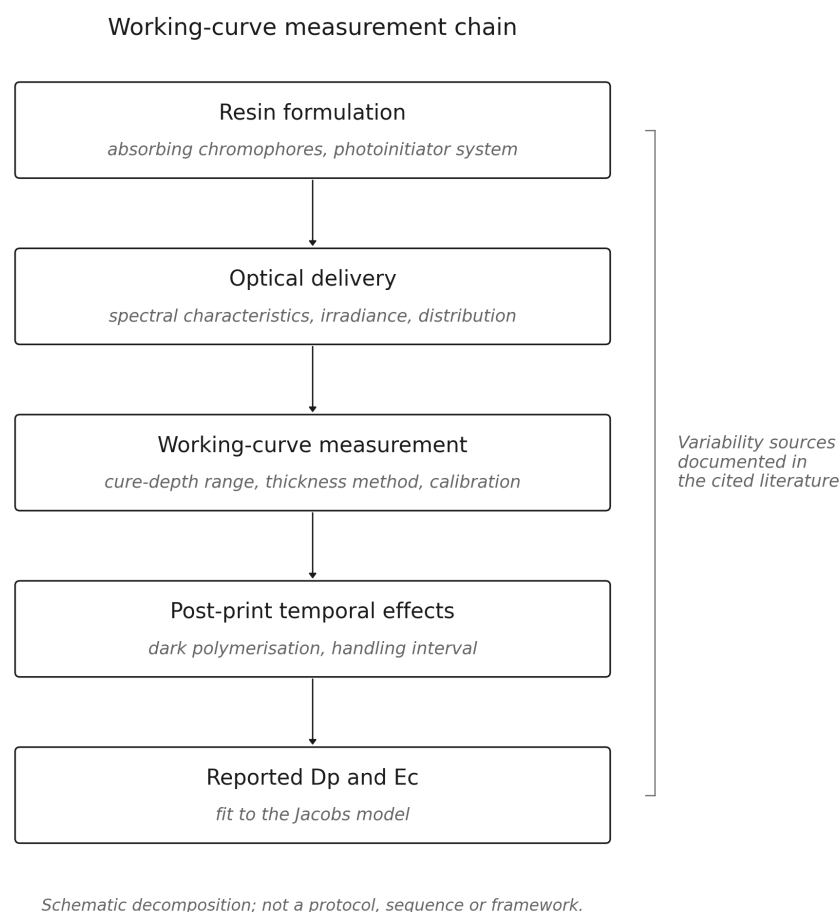


Figure 1

Figure 1. Schematic decomposition of the working-curve measurement chain. The five blocks locate measurement-chain factors discussed in section 4 and in the cited literature [4-12]. The decomposition is conceptual and does not constitute a protocol, sequence or framework. Italic sub-dimensions correspond to factors discussed in sections 4.1-4.4. The bracket indicates that variability can enter at multiple points in the chain; the figure does not imply that every factor has been quantitatively isolated in interlaboratory data.

5. Implications for reporting and process transfer

The evidence synthesised in §3 and the methodological dimensions enumerated in §4 carry implications for two recurring uses of the working-curve measurement: reporting of Dp and Ec in commercial datasheets and the peer-reviewed literature, and transfer of these values between laboratories or between printers.

The first implication concerns the interpretation of reported values. The interlaboratory dispersion documented by Kolibaba and colleagues [4] and the substantial reduction of that dispersion under bandpass-filtered light in the follow-up study [6] support the reading of Dp and Ec as measurement outcomes coupled to the optical conditions under which they are obtained, alongside procedural choices of the measuring laboratory. Reported Dp and Ec values therefore apply most directly to the conditions under which they were measured; transfer to a different optical delivery cannot be evaluated reliably when source spectrum and irradiance conditions are undocumented.

The second implication concerns the spectral dependence of the fit parameters. The polychromatic extension of the Jacobs model by Caplins and colleagues [5] indicates that the apparent Dp and Ec extracted from a working-curve measurement depend on the spectral width and centre wavelength of the source together with the resin absorption profile. The interlaboratory observation of approximately ten nanometres of peak-wavelength variation across five nominally "405 nm" printers [4] shows that nominal wavelength is an incomplete descriptor of optical delivery. Reports that include the emission spectrum of the measuring source are therefore more readily interpretable than reports that identify only a nominal wavelength.

The third implication concerns the intensity at which the measurement is performed. Rudenko and colleagues [7] and Billerbeck and colleagues [8] separately reported intensity-dependent Dp and Ec within single-laboratory measurement series. These results support treating the irradiance at which a working curve is obtained as part of the measurement specification rather than as a passive experimental detail. Reports that include irradiance are therefore more readily comparable across studies than reports in which it is unspecified.

The fourth implication concerns the use of datasheet values across printers. The interlaboratory and spectral studies show that a Dp/Ec pair obtained under one optical configuration is not automatically transferable to another [4-6]. Studies of material-printer working-curve characterisation likewise treat Dp and Ec within a specific material and printer combination [2]. For printer-specific process setup, a working curve measured under the intended optical configuration is therefore more directly applicable than an unqualified datasheet pair.

The directly supported reporting elements include source spectral characteristics, irradiance, exposure or cure-depth range and thickness-measurement method [4-8]. Radiometer spectral characterisation and the interval between exposure and thickness measurement are additional measurement-science considerations supported by [9-12], but their quantitative effects on working-curve dispersion remain unestablished.

6. Limits of the synthesis

The synthesis presented in this Perspective is restricted to the working-curve measurement and to the Jacobs model as the framework under which D_p and E_c are defined. It does not address process control beyond the working curve, post-cure characterisation, mechanical or biocompatibility validation of cured parts, or device-level qualification for any regulated application. The methodological dimensions enumerated in §4 are components of the working-curve measurement chain, not components of a broader photopolymer additive manufacturing workflow.

The two NIST interlaboratory studies [4,6] and the polychromatic extension of the Jacobs model [5] are the principal empirical anchors of the synthesis. The intensity-dependence observations of Rudenko and colleagues [7] and Billerbeck and colleagues [8] provide additional single-laboratory evidence for one methodological dimension. Systematic interlaboratory reproduction of comparable variability data outside the NIST coordination has not, to the author's knowledge, been reported to date. The synthesis is therefore anchored on a small number of peer-reviewed studies, and its generalisability to all vat-photopolymerisation operational contexts is not established.

The spectral and irradiance dependencies are directly supported by working-curve studies [4-8]. Radiometer spectral mismatch and post-exposure polymerisation are supported by radiometric and photopolymerisation literature [9-12], but their quantitative contributions to working-curve interlaboratory dispersion have not been isolated. The measurement-chain decomposition in section 4 is therefore a synthesis of evidence at different levels, not a validated calibration procedure or measurement protocol, and it is not proposed as such here.

The boundary between observation and interpretation is set as follows. The observation is that the working-curve fit parameters D_p and E_c , as reported in the cited studies, vary substantially across laboratories under unfiltered measurement conditions, vary less under bandpass-filtered conditions, and depend on the light intensity at which the measurement is performed in separately reported single-laboratory studies. The interpretation is that these observations are consistent with D_p and E_c being coupled to the measurement spectrum, irradiance and procedure rather than behaving as material constants in the strict sense.

The relative contribution of each methodological dimension under different operational conditions, the dependence of these contributions on resin chemistry, and the extension of the working-curve framework to processes that depart from the Jacobs assumptions in additional respects are not addressed by the present synthesis.

7. Conclusions

The working-curve measurement is a foundational characterisation of resin behaviour in vat photopolymerisation, and its two fit parameters, D_p and E_c , are routinely reported as material properties on commercial datasheets and in the peer-reviewed literature. The interlaboratory studies coordinated by the National Institute of Standards and Technology [4,6], the polychromatic extension of the Jacobs model by Caplins and colleagues [5], and the separately reported intensity-dependence observations of Rudenko and colleagues [7] and Billerbeck and colleagues [8] together indicate that D_p and E_c , as currently measured, vary with the spectral characteristics of the light source, can vary with irradiance for at least some resin systems, and are sensitive to procedural choices of the measuring laboratory.

The methodological reading supported by this evidence is that D_p and E_c , when extracted from a working-curve measurement under current vat-photopolymerisation hardware, are coupled to the spectrum, irradiance and procedure of that measurement rather than behaving as material constants in the strict sense. Reporting elements directly supported by working-curve studies include source spectrum, irradiance, exposure or cure-depth range and thickness-measurement method [4-8]. Radiometer spectral characterisation and the post-exposure handling interval are additional considerations from measurement-science and polymerisation literature whose quantitative contributions to working-curve dispersion remain to be established [9-12].

The synthesis does not address the relative contribution of each methodological dimension under different operational conditions, nor the extension of the working-curve framework to processes that depart from the Jacobs assumptions in additional respects. The methodological dimensions enumerated here are documented components of the working-curve measurement chain in the cited studies and are not proposed as a calibration procedure, a measurement protocol or a standard.

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Not applicable.

Disclosure / Declaration of Competing Interest

The author is the founder and Scientific Director of Resyner Technologies S.L. (3Dresyns), a company that produces photopolymer materials for vat photopolymerisation. This Perspective synthesises peer-reviewed publications from independent research groups, including studies published in Additive Manufacturing. No commercial product is cited, recommended or otherwise referenced in this manuscript. The synthesis does not propose a new standard, framework or protocol.

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