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Effect of Layer Exposure Time in SLA-LCD Printing on Surface Topography, Hardness and Chemical Structure of UV-Cured Photopolymer

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Abstract

The exposure parameters in stereolithography with liquid crystal display (SLA-LCD) influence the functional properties of photopolymers, which is particularly important for tribological applications. In this study, the influence of the exposure time of the layers (2–8 s) on the surface topography (ISO 25178), Brinell hardness (HB) and chemical structure (FTIR spectroscopy) of UV-cured resin samples is investigated. Both insufficient and excessive UV irradiation led to undesirable effects ranging from incomplete cross-linking and surface irregularities to excessive curing, micro-cracking and increased surface kurtosis (high Sku values). The most balanced mechanical and topographical performance was observed at a layer exposure time of 6 s, characterised by low Spk values, uniform surface texture and high cohesion between layers. FTIR analysis confirmed the progressive cross-linking with increasing exposure time. The results show that precise control of irradiation parameters enables optimisation of the interrelationships between microstructure, mechanical properties and surface functionality, which is critical for improving the durability and performance of components operating under boundary or mixed lubrication.

Keywords: SLA-LCD; 3D printing; surface topography; hardness of photopolymers; tribological performance

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1. Introduction

In recent years, additive manufacturing (AM) has evolved from a method primarily used for rapid prototyping to a manufacturing process capable of producing functional, high-performance end-use components. Among the various AM processes, stereolithography (SLA) is a leading technique due to its ability to produce highly detailed, complex geometries with excellent surface finish and dimensional accuracy [1]. These advantages make SLA a strong candidate for applications requiring precision, e.g., biomedical devices, soft robotics, jewellery design or aerospace applications [2]. SLA is based on photopolymerisation, in which UV light selectively cures a liquid resin layer by layer.

1.1. SLA-LCD Process

The SLA process usually begins with the digital decomposition of a 3D computer-aided design (CAD) model into a series of two-dimensional (2D) cross-sectional layers. A typical SLA setup includes a resin container, a UV light source and a movable build

platform. The photopolymer resin is poured into the container and the build platform is initially positioned just above the transparent bottom of the container, close to the resin surface. After each layer has been cured, the build platform moves slightly upwards so that uncured resin can flow underneath. The next layer is then exposed and polymerised in the same way. This process is repeated until the entire 3D structure is moulded. To ensure structural stability during printing, especially in overhanging or unsupported areas, support structures are generated from the CAD model and produced at the same time as the object. After printing, the supports are removed manually.

1.2. Importance and Effect of UV Parameters

The printed part is then cleaned with a solvent such as isopropanol to remove any uncured resin [3]. Although this process is well established, the precise tuning of UV exposure parameters remains a major challenge. The wavelength, intensity and exposure time of the UV radiation directly influence the degree of polymer conversion, the cross-linking density and the mechanical cohesion between the layers [4]. An important aspect that determines the overall performance of the SLA process is the type of ultraviolet (UV) light source used to initiate photopolymerisation. Among the wavelengths commonly used in SLA systems, 365 nm, 385 nm, and 405 nm are the most prevalent [5]. However, the printed models with the light source with ~405 nm are characterized with the best modulus and tensile strength [6]. Beyond wavelength selection, the duration of UV exposure not only influences the depth of cure and mechanical strength, but also leads to compromises in brittleness, resolution and surface morphology [7,8]. Insufficient exposure time can lead to incomplete polymerization, resulting in weak interlayer bonding and residual monomers that may compromise mechanical stability or biocompatibility. For example, Aznarte et al. [9] found that during resin-based 3D printing technologies elastic modulus decreased with lower exposure times. In contrast, a too long time of curing may cause an increase in stiffness and conversion degree and a decrease in the resolution [10]. Moreover, high exposures result in a increase in the force needed to raise the printed model from the vat, which may lead to delamination problems [11].

1.3. Relevance of Parameter Control for Functional Applications

As such defects may also manifest at or near the surface, analysing the surface topography provides valuable insights into the morphological quality and structural integrity of the printed parts. Precise control of exposure conditions is particularly important for functional applications where surface integrity and mechanical reliability are critical. This is especially relevant for components subjected to abrasive or frictional loading conditions, where microstructural uniformity and appropriate cross-linking density are key determinants of wear resistance. In our previous study [12], we investigated the effects of different exposure times on the abrasion resistance of SLA LCD-printed elements. The results indicated a deterioration in wear behaviour with longer exposure times, most likely due to increased brittleness and excessive cross-linking density at the surface. Although previous studies have investigated the general effects of UV curing on mechanical properties, the relationship between exposure time, surface microstructure and functional performance, especially for tribologically loaded components, is still not well understood. This is particularly important for SLA-printed parts operating under frictional or sliding contact, where surface integrity and chemical homogeneity determine long-term reliability [11].

Surface geometric parameters (SGP) are of central importance for tribological applications, influencing friction, lubrication regimes, and wear mechanisms. Following the ISO 25178 standard, roughness metrics can provide a detailed insight into surface integrity and printing artefacts [13]. In addition, Fourier-transform infrared (FTIR) spectroscopy offers a

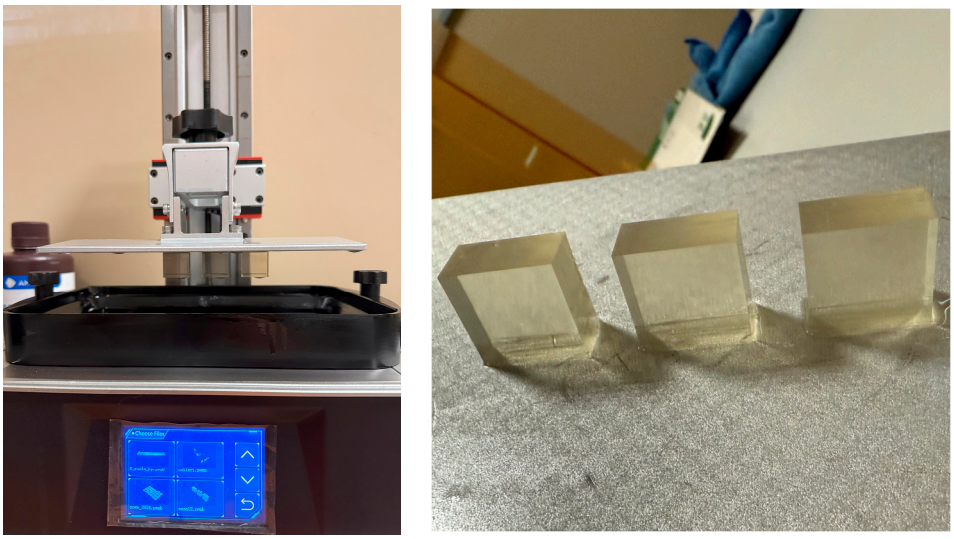
non-destructive method to assess UV-induced chemical transformations, especially changes in functional groups such as C=O, C=C, or OH, which are indicative of polymer cross-linking progression. Finally, hardness measurements, e.g., via Brinell indentation, serve as a practical metric for evaluating mechanical robustness, particularly when assessing the influence of varying UV doses on the cured polymer network.

To address this gap, this study investigates the influence of UV layer exposure time in SLA LCD printing on the surface topography, chemical structure and mechanical performance of a standard photopolymer resin. Using a combined approach of 3D surface analysis (ISO 25178), FTIR spectroscopy and Brinell hardness testing, we aim to establish clear structure–property–process relationships relevant for the optimisation of SLA parameters for functional applications.

2. Materials and Methods

2.1. Materials Used and Printing Process

The specimens were printed with a transparent photopolymer resin (Anycubic) designed for SLA-LCD printing technology at a wavelength of 405 nm. The printing process was carried out with an Anycubic Photon Mono 6K (Shenzhen Anycubic Technology, Shenzhen, China) printer, which offers an XY resolution of 34 µm and a layer height of 50 µm. According to the recommendations of both the resin and printer manufacturers, the typical curing window for a 50 µm layer at 405 nm wavelength is 2–8 s. These values are considered optimal for this type of resin–printer system, balancing efficient curing and practical printing time. Since SLA-LCD printed models consist of many successive layers, any increase in exposure time proportionally extends the total printing duration and thus production costs. Based on the manufacturer's guidelines and preliminary trials, four exposure times were selected for this study: 2 s (T2), 4 s (T4), 6 s (T6), and 8 s (T8). For each exposure time, three rectangular specimens were prepared, each measuring 10 × 20 × 20 mm (Figure 1).



(**a**) (**b**)

Figure 1. (**a**) SLA-LCD printer (Anycubic Photon Mono 6K) at the end of the printing process, with the build platform elevated; (**b**) specimens obtained from the printing process.

Printing was performed under controlled ambient conditions (T = 23 ± 1 °C, RH = 45–50%). After printing, the specimens were cleaned with an isopropanol mist for 60 s to remove residual uncured resin. No additional UV post-curing was performed to avoid introducing a

confounding variable into the evaluation of exposure time effects. The de-tailed processing parameters for all printing variants are summarized in Table 1.

Table 1. SLA-LCD printing parameters.

Parameter	Value/Setting
Printer model	Anycubic Photon Mono 6K
Resin type	Anycubic Transparent Photopolymer
Light source wavelength	405 nm
XY resolution	34 μm
Layer height	50 μm
Ambient conditions	23 ± 1 °C; RH = 45–50%
Cleaning	Isopropanol mist, 60 s
Post-curing	None
Exposure time per layer	2 s (T2), 4 s (T4), 6 s (T6), 8 s (T8)

2.2. The Geometric Structure of the Surface

The geometric structure of the surface was analysed using a contact profilometer Mitutoyo Formtracer Avant S-3000(Mitutoyo, Kawasaki, Japan) equipped with a stylus with a tip angle of 60° and a tip radius of 2 μm. Measurements were performed in grid mode over an area of 5 × 5 mm at a scanning speed of 0.5 mm/s. Each specimen was scanned in two perpendicular directions (X and Y). The data was processed using MCubeMap software (v.8) in accordance with ISO 25178-2. The analysis included height parameters (Sa, Sq, Sku) and functional parameters (Spk, Svk, Sk, Smr1, Smr2). The study was complemented by imaging in opto-SEM mode using a Keyence VHX-7000 (Keyence, Osaka, Japan) digital microscope. Images were acquired at 500× magnification under directional side illumination. This imaging method allowed the evaluation of the interlayer structure and surface defects. Both profilometric and opto-SEM analyses were performed in the central region of the lateral surface of the specimens, corresponding to a location 10 mm above the base and 10 mm from the side edge.

2.3. Hardness

The hardness test was carried out using an Innovatest Nexus 703A(INNOVATEST Europe BV, Maastricht, The Netherlands) hardness tester equipped with a 2.5 mm diameter spherical indenter. The dwell time of the load was 15 s. Ten measurements were performed for each variant. The measured values were recorded automatically according to the manufacturer's calibration procedure.

2.4. Fourier-Transform Infrared Spectroscopy (FTIR)

The FTIR spectra were recorded in the 4000–400 cm^{-1} range using a Spectrum Two FTIR spectrometer (PerkinElmer, Waltham, MA, USA) in attenuated total reflectance (ATR) mode. In addition to the general spectral analysis, selected absorption bands corresponding to functional groups C=O (~1720 cm^{-1}), C=C (~1635 cm^{-1}) and OH (3200–3600 cm^{-1}) were analysed to evaluate differences in polymer cross-linking and transformation between specimens prepared with different exposure times.

3. Results and Discussion

Analysis of the SLA-LCD printed samples exposed to different UV exposure times revealed differences in the morphology of the layers and the surface topography, as shown by opto-SEM imaging (Figure 2) and 3D surface mapping (Figure 3). These differences highlight the role of exposure time in determining the structural and mechanical integrity of the printed objects. Specimen T2, which was cured with the shortest specific exposure

time per layer, exhibited pronounced morphological defects. Opto-SEM images revealed irregular bulging of the layers, discontinuous interlayer boundaries and wavy deformation patterns (Figure 2a). These features indicate insufficient polymerization leading to insufficient adhesion between the layers and local softening of the material. The 3D topography (Figure 3a) confirmed strong height differences and anisotropic irregularities probably caused by internal stresses during successive resin coating cycles [12]. Furthermore, the presence of discontinuous boundary lines could be due to the limited resolution of the LCD mask, especially at the pixel edges, where incomplete exposure could prevent uniform curing. Overall, these results suggest that the resin does not achieve complete cross-linking at very short exposure times, resulting in dimensionally inaccurate structure.

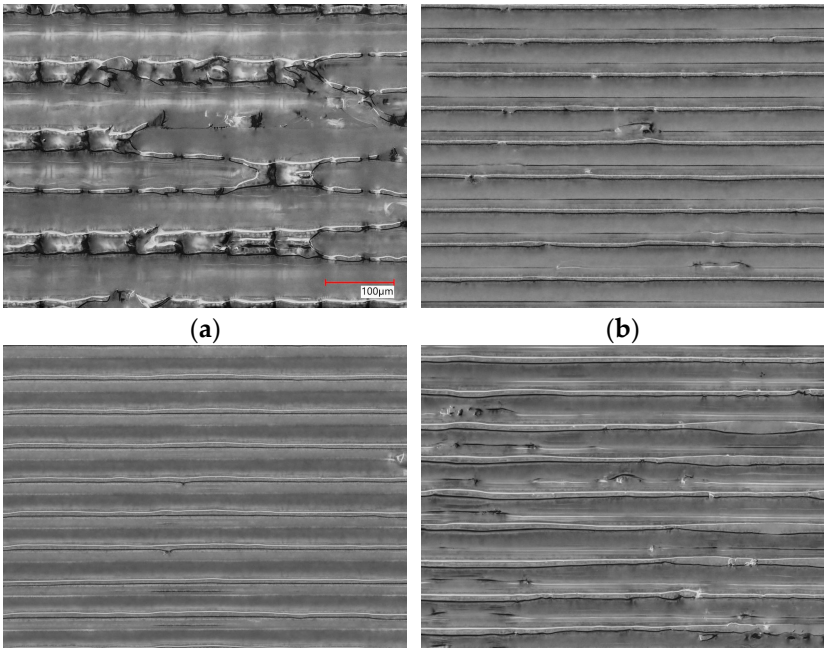


Figure 2. Micrography opto-SEM mode of SLA-LCD printed samples cured under different exposure times: (**a**) T2—2 s, (**b**) T4—4 s, (**c**) T6—6 s, (**d**) T8—8 s. All images were acquired at 500× magnification using the same scale bar.

In contrast, sample T4 showed a visibly improved morphology compared to T2 (Figure 2b). The layer boundaries were more clearly defined, the surface appeared smoother and the frequency of defects was markedly reduced in comparison to T2. Topographic analysis showed a more uniform height distribution and the absence of abrupt transitions, indicating a more complete, albeit not yet ideal, cross-linking process (Figure 3b). Nevertheless, occasional point defects and residual waves indicate that although the curing process had improved compared to T2, the optimal parameters had not yet been reached. Sample T6 exhibited the highest structural quality under the conditions tested (Figure 2c). Both the opto-SEM image and the 3D surface profile showed a well-organized, repeating layered pattern with minimal deformation (Figure 3c). The surface was smooth, without sharp protrusions or depressions, and free of microcracks or discontinuities. These characteristics indicate that the UV curing process under these conditions resulted in an optimal degree of polymerization and formed a stable and continuous network with high mechanical cohesion. This observation aligns with previous studies highlighting the importance of optimizing light exposure parameters to ensure structural consistency and material performance in photopolymer-based 3D printing [14,15]. In the present study, it is shown that an exposure time of 6 s allows the formation of a sufficiently cross-linked resin matrix that can

withstand internal stresses without deformation or fracture. Extending the exposure time to 8 s for sample T8 (Figure 2d) led to a deterioration in surface quality. Opto-SEM analysis showed microcracks along the interlayer boundaries and irregular geometric deformations, while 3D topography (Figure 3d) revealed increased surface roughness and sharper height transitions. These features indicate overhardening of the resin, which can lead to excessive brittleness and internal stress accumulation due to supersaturation of the cross-linked network [7]. Such changes impair the elasticity and resilience of the material and shorten its overall service life. These results reinforce the notion that excessive exposure can be as detrimental as insufficient curing, especially when mechanical flexibility and resistance to crack propagation are desired.

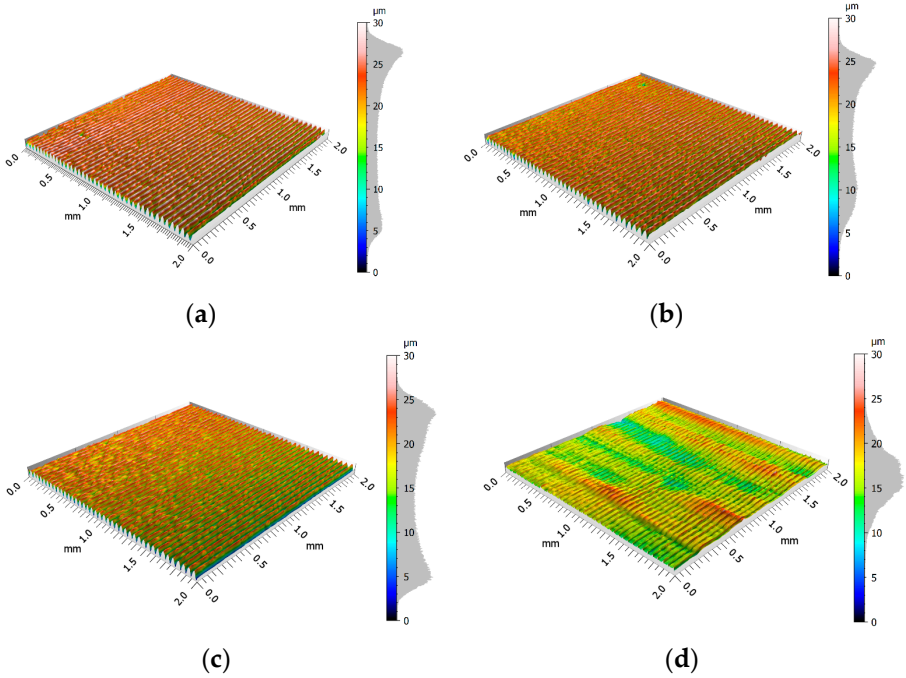


Figure 3. 3D surface topography maps of SLA-LCD printed samples cured under different exposure times: (**a**) T2—2 s, (**b**) T4—4 s, (**c**) T6—6 s, (**d**) T8—8 s.

The analysis of the quantitative surface parameters (Table 2) supports the observations obtained from the 3D topographic maps. The highest surface roughness was observed in sample S2, where irregular peaks and localized layer deformations were observed (Figure 3a). A decrease in Sa and Sq values in sample S4 indicates a partial smoothing of the surface, which correlates with the more ordered structure in Figure 3b (Table 2). The highest degree of texture uniformity was observed in sample S6 (Figure 3c), which is reflected in the lowest kurtosis (Sku = 1.66) and a relatively low peak height (Spk = 1.17 µm). The functional core roughness depth (Sk = 19.17 µm) reaches the maximum among all samples and indicates a deep and robust support structure that can positively influence the contact stability and load-bearing capacity. The lowest gap depth observed in this sample (Svk = 4.58 µm) could indicate a reduced ability to absorb liquids, including lubricants; however, this effect is compensated by the low Spk value and the high structural regularity. The surface texture not only reflects the degree of photopolymer conversion, but also reveals the microstructural durability of the cured material, which is crucial for tribological applications. Sample S8 exhibits an unusual combination of characteristics: While Sa and Sq reach minimal values (3.94 µm and 5.28 µm, respectively), the other parameters indicate a deterioration in functional performance. In particular, the strikingly high Spk value of 5.30 µm—more than four times higher than the other samples—indicates the formation of

sharp peaks, which may increase initial wear during tribological operation. The increase in Sku to 4.68 confirms the presence of extreme height values corresponding to these sharp features. A decrease in Smr2 to 12.3% (compared to 32.84% for S2) indicates a lower ability to retain lubricant, while the Smr1 value of 13.17% suggests that the actual contact area is dominated by pronounced peaks, which is undesirable under dry friction conditions.

Table 2. Surface texture parameters (ISO 25178) of SLA-LCD printed samples as a function of UV exposure time.

Exposure Time [s]	Surface Texture Parameters							
	Sa	**Sq**	**Sku**	**Spk**	**Svk**	**Sk**	**Smr1**	**Smr2**
2	6.30	7.19	1.89	1.12	10.82	13.16	1.68	32.84
4	5.16	5.90	2.00	1.15	5.90	13.65	1.84	25.51
6	6.50	7.32	1.66	1.17	4.58	19.17	1.64	21.23
8	3.94	5.28	4.68	5.30	7.97	10.99	13.17	12.30

The surface hardness test revealed a relationship between the exposure time and hardness or printed objects, which was measured using the Brinell method.

The mean Brinell hardness values for samples exposed for 2, 4, 6 and 8 s were 53.07, 57.63, 67.60 and 75.33 HB, respectively (Figure 4). The largest increase was observed between the 2 s and 8 s variants, where the hardness increased by 22.26 HB, corresponding to a relative increase of 41.9%. The average increase in hardness per second of exposure time (ΔHB/s) was 3.71, indicating an almost linear increase in the degree of hardness of the material within the analysed range of processing parameters. However, the rate of change was not constant: a moderate increase of 8.6% was recorded between 2 and 4 s, while a more significant increase of 11.4% occurred between 6 and 8 s, indicating a non-linear saturation of the polymer network. The standard deviation of the measured values varied between the samples. The lowest variability was observed in the 4-second exposure group (SD = 1.38), which could indicate a stable course of photopolymerization in this range. In contrast, the greatest measurement scatter was observed in the 6-second samples (SD = 4.24), which could be due to microstructural heterogeneity as the material approaches the threshold energy required for efficient crosslinking.

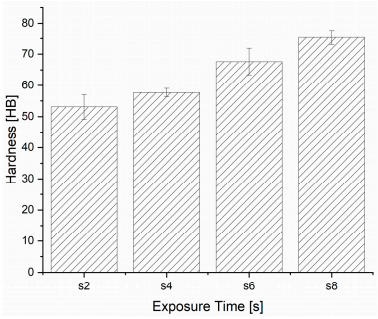


Figure 4. The effect of ultraviolet radiation exposure time on hardness.

The evaluation of the FTIR (Figure 5) spectra of all samples showed changes in their chemical structure depending on the UV exposure time. The data were normalized to the reference band at ~1720 cm^{-1}, which corresponds to the stretching vibrations of the carbonyl (C=O) groups in acrylate esters, allowing an assessment of the relative changes in other characteristic photopolymerization bands. In the range of 1635–1610 cm^{-1}, a systematic decrease in the intensity of the band associated with the C=C stretching vibrations was observed, indicating an increasing degree of vinyl bond conversion with longer exposure time. The decreasing signal is consistent with the crosslinking mechanism

of acrylate-based photopolymers described by Li et al. and Wu & Halloran [1,2]. The 1450–1400 cm^{-1} region, assigned to the deformation vibrations of methyl and methylene groups (CH_2/CH_3), showed stable band position in all samples. The lack of fluctuations in this range confirms the integrity of the aliphatic side chains and indicates that the curing process does not affect these polymer segments. In the 1250–1000 cm^{-1} range, corresponding to the C–O–C and C–OH stretching vibrations, this change could indicate an increasing contribution of ether bridges within the developing polymer network. This secondary phenomenon following the decrease in C=C signal is consistent with the observations of Zhang et al. [4]. In the range 3020–2800 cm^{-1}, which includes the stretching vibrations of the –CH_3 and –CH_2 groups, the spectra remained virtually unchanged, with no visible shifts or intensity changes. This indicates that the main chain is not degraded and emphasizes the stability of the side segments under prolonged exposure conditions [3]. In particular, changes were recorded in the 970–810 cm^{-1} range, where the gradual disappearance of the band at ~815 cm^{-1} associated with =C–H (trans-vinyl) vibrations clearly confirms the conversion of double bonds. This is typical of acrylate photopolymerization, which has been reported previously [1,2]. The data collected clearly indicate that the predominant mechanism of chemical modification over the range of exposures tested is the transformation of unsaturated bonds while maintaining the integrity of both backbone and side chain structures.

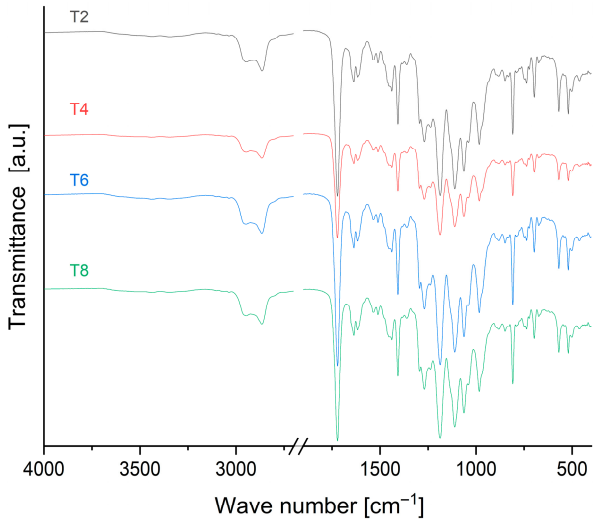


Figure 5. The FTIR spectra of SLA-LCD printed samples cured under different exposure times: T2—2 s, T4—4 s, T6—6 s, T8—8 s.

To investigate the relationship between the progress of the cross-linking reactions and the hardness of the material, a comparative analysis was performed using the intensity of the FTIR band corresponding to the C=C double bonds (1635–1610 cm^{-1}) and the Brinell hardness (HB). Both parameters were modelled by linear regression concerning UV exposure time. The resulting regression equations showed a strong correlation, negative for FTIR (r = –0.999) and positive for HB (r = 0.991), confirming the expected inverse relationship between these indicators (Figure 6). The decreasing intensity of the C=C binding signal, consistent with the photoinitiated conversion of vinyl groups, correlated strongly with the increase in material hardness resulting from the progressive crosslinking of the polymer network. The regression slope for the FTIR signal was –9.57 ± 0.23 (%/s), while for hardness it was +7.23 ± 0.69 (%/s), reflecting the contrasting nature of physicochemical and mechanical changes during the curing process. The high coefficients of determination (R^2_FTIR = 0.999; R^2_HB = 0.982) confirm the statistical significance of the observed trends. This comparison shows that FTIR spectroscopy can be used as both a qualitative and

quantitative indicator of curing progress and allows prediction of mechanical properties without the need for destructive testing.

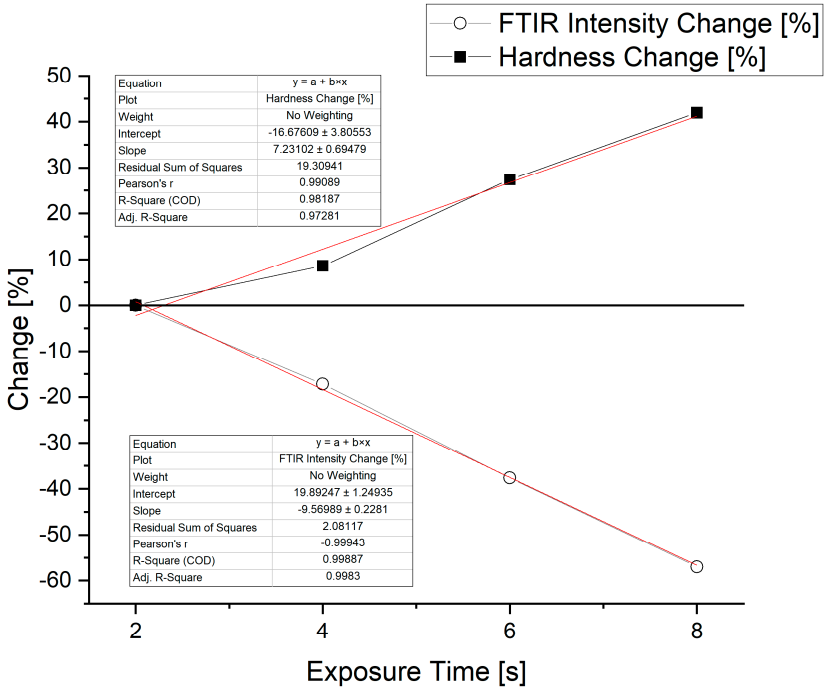


Figure 6. The relationship between the progress of the cross-linking reactions and the hardness of the material. The red lines indicate trend lines fitted to the experimental data.

4. Conclusions

The results show a clear correlation between UV exposure time and the resulting morphology and surface properties of parts printed with SLA-LCD. An exposure time of 6 s (T6) seems to offer the most favourable balance and leads to geometrically accurate and mechanically reliable structures. Both insufficient and too long exposure times lead to morphological defects and affect material properties, emphasizing the need for precise exposure control in photopolymer-based additive manufacturing. Future work should focus on quantitative correlations between cross-linking density, mechanical performance and curing parameters, possibly incorporating in-situ diagnostics or adaptive exposure control systems for real-time optimization.

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Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AM	additive manufacturing
SLA	stereolithography
SLA-LCD	Liquid Crystal Display SLA print
CAD	computer-aided design
UV	ultraviolet
2D	two-dimensional
SGP	surface geometric param
FTIR	Fourier-transform infrared
RH	relative humidity

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