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IMPACT OF PRINTING PARAMETERS AND POST-CURING ON SURFACE QUALITY IN MSLA 3D PRINTING

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Abstract: This study experimentally investigates the effects of printing parameters and post-curing on the surface roughness of photopolymer-based parts produced using the masked stereolithography (mSLA) method. Parameters such as layer thickness (0.02–0.04 mm), exposure time (3–5 s), and printing angle (0–45°) were determined using an L9 Taguchi orthogonal design, and both as-printed and post-cured samples were produced for each combination. Surface roughness was measured in areal (Sa) format using an optical profilometer, and the data were evaluated using analysis of variance (ANOVA) and SN ratios. The findings showed that surface roughness was mostly affected by layer thickness, followed by printing angle, while exposure time had a limited effect. The lowest Sa value was obtained with a layer thickness of 0.02 mm, an exposure time of 3 s, and a printing angle of 0°. Post-curing reduced surface roughness by 8–11% in all groups. However, the magnitude of this improvement depends on the initial surface irregularity. Consequently, it has been demonstrated that both printing and curing parameters should be optimized in applications requiring high surface quality.

Keywords: Additive manufacturing, 3D mSLA printing, Print parameters, Post-curing, Surface roughness

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1. Introduction

Additive Manufacturing (AM) has gained significant interest in industry, research, and hobbyists over the past few decades. This is because it allows for the rapid and easy production of more complex and irregular products than those achievable with traditional manufacturing methods, enabling mass production while simultaneously saving material and time (Choudhari and Patil, 2016; Haldar, 2023; Abbasi et al., 2025). Stereolithography (SLA), an AM technology that utilizes liquid resins, has emerged as one of the high-precision 3D printing technologies for manufacturing. Particularly suited for applications requiring high resolution and accuracy, high-speed printing, and good surface quality, SLA is a process that selectively cures layers of liquid photopolymer resin using ultraviolet (UV) light (Melchels et al., 2010; Ngo et al., 2018; Albaşkara, 2025). Many high-precision applications, from medical implants to microfluidic devices, rely on SLA technology (Pop et al., 2022; Biswas et al., 2024). Printed SLA objects undergo multiple stages before use. Curing is a post-printing process to improve mechanical and physical properties (Cheadle et al., 2025). This reaction is often facilitated by high-energy UV irradiation. This process increases the structure's rigidity and directly impacts dimensional stability, water resistance, biocompatibility, and surface properties (Jiang et al., 2020; Arefin et al., 2021; Ali et al., 2024; Azani and Hassanpour, 2024). Surface roughness is one of the most critical quality parameters directly affected by post-curing. While SLA printing surfaces are generally smooth, internal stresses in the resin, the layered manufacturing structure, and post-curing shrinkage or surface tension can lead to undesirable micro-roughness on the surface (Albaşkara and Türkyılmaz, 2023; Golhin et al., 2023). These inconsistencies can reduce the material's surface quality and the part's functionality. Post-curing, applied to increase the strength and dimensional stability of resin-based parts after printing, causes microstructural changes on the part's surface, directly affecting surface roughness (Aati et al., 2022; Baytur and Diken Turksayar, 2025).

Mukhangaliyeva et al. (2023) evaluated the surface roughness and dimensional accuracy of parts produced using SLA based on parameters such as layer thickness, build angle, support density, and model orientation. The findings showed that the factor that most significantly affected surface roughness was build angle, followed by layer thickness. The best surface quality was achieved with a layer thickness of 0.025 mm, a build angle of 0°, and positioning the model parallel to the printer table. These results suggest that thin-layer and low-angle printing strategies should be preferred for high surface quality in the SLA process. Singh et al. (2023)

investigated the effects of parameters such as layer height, exposure time, light-off delay, and print orientation on the dimensional accuracy and surface roughness of parts produced using m-SLA technology. The analyses revealed that layer height and print orientation had the most significant impact on surface roughness and were also related to dimensional reduction and print duration. The smoothest surfaces were achieved with low layer height and horizontal print orientation. Dhingra et al. (2025) conducted a comprehensive study to determine the influencing parameters on the surface roughness and dimensional accuracy of parts produced using SLA 3D printing technology. Parameters such as layer thickness, print orientation, exposure time, and curing time were considered in the study, and the Response Surface Methodology (RSM) was used as the experimental design. The findings showed that increasing layer thickness significantly increased surface roughness, while print orientation was a determining factor in both surface quality and dimensional accuracy. The lowest roughness and deviation values were achieved with a layer thickness of 0.05 mm and a print orientation of 0°. Furthermore, improvement in surface quality was observed with increased curing time, but microscopic cracking tendencies were reported in the material at excessive times.

Studies in the literature have shown that printing parameters significantly affect surface roughness. Furthermore, post-curing is also known to affect surface roughness significantly (Al-Dulaijan et al., 2022; Yoo et al., 2024). Therefore, understanding the relationship between printing parameters and post-curing is crucial. Parameters such as layer height, exposure time, and build angle significantly impact surface roughness.

The main objective of this study is to examine the interaction between the printing parameters layer height (LH), exposure time (ET), and build angle (BA) and the post-curing process on surface quality. Although numerous studies have investigated the influence of printing parameters or post-curing conditions separately on surface quality in SLA-based systems, the interactive relationship between these two stages has not been sufficiently quantified. Most existing research focuses either on process parameter optimization during printing or on post-processing improvements. However, surface morphology in mSLA is inherently the result of a sequential, interdependent manufacturing chain, in which post-curing acts on a surface structure already shaped by printing parameters. Therefore, the novelty of this study lies in treating printing and post-curing not as independent factors but as an integrated, interactive system. By quantitatively evaluating both the direct effects of process parameters and their influence on post-curing-induced improvements (ΔSa), this study provides a more holistic understanding of surface quality formation in mSLA.

2. Materials and Method

2.1. Equipment and Production of Samples

Samples were printed on an Elegoo Saturn 3 mSLA printer (Figure 1a) with printing parameters determined according to the Taguchi L9 orthogonal array given in Table 1. The selected parameter ranges were determined considering both applicability and literature studies. Layer thickness values (0.02–0.04 mm) are frequently used and recommended values in mSLA printing. Exposure time (3–5 s) was chosen within the manufacturer's recommended curing range for 405 nm photopolymer resin to ensure sufficient interlayer adhesion while avoiding excessive polymerization effects, and is also frequently used. Print angle levels (0–45°) were selected to represent horizontal, moderately inclined, and highly inclined configurations, which are known to affect step effects and surface morphology. Thus, by determining the most commonly used parameter range values, the effect of post-curing on the surface quality of the parts could be investigated. Cured and as-printed samples were printed simultaneously in three 10 mm cube sizes for each parameter to ensure standard production. Anycubic white resin with a wavelength of 405 nm was used as the resin material. After printing, the samples were cleaned with IPA for 5 minutes on the Anycubic Clean and Wash 2.0 device and then post-cured at a wavelength of 405 nm (Figure 1b). Curing was performed for 15 minutes for each sample.

Table 1. Printing parameters according to L9 orthogonal array

Exp. No	LH (mm)	ET (s)	BA (°)
1	0.02	3	0
2	0.02	4	30
3	0.02	5	45
4	0.03	3	30
5	0.03	4	45
6	0.03	5	0
7	0.04	3	45
8	0.04	4	0
9	0.04	5	30

2.2. SR Measurements

Surface roughness changes of cured and as-printed samples with the same printing parameters were determined using area (Sa) measurements on a Nanovea ST400 device. Scanning was performed in single direction with a scan distance of 1 µm. Nanovea Professional 3D software was used with a spline filter and a cut-off value of 80 µm. A 0.2x0.2 mm area was scanned from the lateral surfaces of the printed layers of the samples, and three measurements were taken for each sample. The Sa value for each test was determined by averaging the measurements.

Figure 1. Overview of the SLA printing (a) and post-curing setup (b).

3. Results and Discussion

As-printed and cured surface roughness values, with improvement and ΔSa values, for parts produced using the 3D mSLA method are presented in Table 2. The table demonstrates that the surface quality of the cured parts improved compared to the as-printed parts. The improvement values were calculated as percentages. The highest improvement was observed in the 6th experimental parameter, while the lowest improvement was observed in the 8th experimental parameter. However, the improvement values are quite similar. One of the most striking findings of this study is that post-curing reduced surface roughness by 8–11% across all printing parameters. ΔSa is the difference in surface roughness between cured and as-printed samples. The decrease in Sa values in the post-cured samples indicates that complementary polymerization under UV light partially eliminated micro-indentations and protrusions on the surface, transforming the surface into a more homogeneous structure. ΔSa values, particularly at high layer height and high build angle combinations, reach their highest values, indicating that the post-curing effect depends on the size of the initial surface defects. Thus, parts with higher initial roughness benefit more from post-curing.

Table 2. Surface roughness results

Exp. No	Sa (As-printed) (µm)	Sa (Cured) (µm)	Improvement (%)	ΔSa
1	0.428	0.385	10.05	0.043
2	0.472	0.423	10.38	0.049
3	0.634	0.573	9.62	0.061
4	0.605	0.549	9.26	0.056
5	0.671	0.608	9.39	0.063
6	0.593	0.531	10.46	0.062
7	0.806	0.724	10.17	0.082
8	0.742	0.683	7.95	0.059
9	0.819	0.743	9.28	0.076

Comparing the 3D surface morphology of the 6th experimental sample, which showed the highest improvement in Figures 2(a) and 2(b), reveals a more homogeneous height distribution and a lower microprotrusion density, resulting in a significant reduction in peaks and valleys on the surface after post-curing. This is attributed to the complete cross-linking of the polymer chains and the elimination of partial surface sags.

In contrast, in the sample with the lowest improvement in Figures 2(c) and 2(d), post-curing resulted in limited surface softening, but the high peaks were largely preserved. This suggests that the initial printing defects of this sample were not fully eliminated by post-curing, and that surface roughness is more sensitive to material/printing parameters.

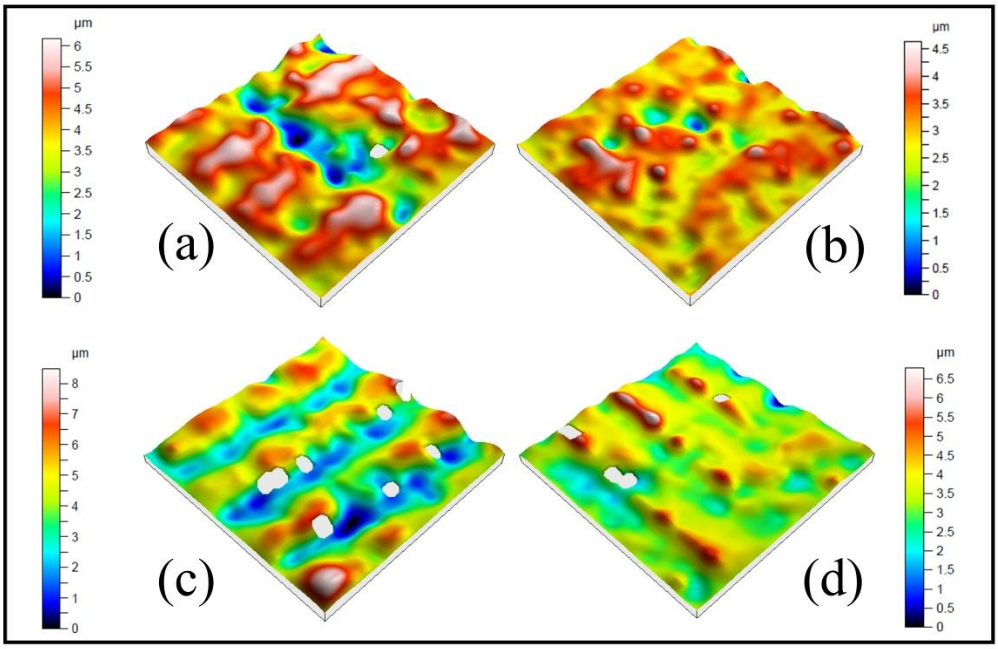

Figure 2. 3D surface profiles of (a) the highest improvement sample as-printed and (b) post-cured, (c) the lowest improvement sample as-printed, (d) and post-cured.

3.1. SR Analysis of As-printed Samples

The results of Taguchi analysis for the surface roughness of as-printed parts are presented in Table 3. According to the results, layer height is the most influential parameter on the surface roughness of as-printed parts. This is due to the stair-step effect of the mSLA method (Singh et al., 2023; Golhin et al., 2023). Build angle is the second most influential parameter, particularly due to the stair-step effect at high angles. Exposure time is the least influential parameter.

Table 3. Taguchi analysis of as-printed samples

Level	LH	ET	BA
1	5.950	4.536	4.834
2	4.123	4.193	4.207
3	2.067	3.410	3.099
Delta	3.884	1.126	1.735
Rank	1	3	2

When the SN ratio plot in Figure 3, which shows the effects of the parameters and their optimum levels, is examined, the initial levels of all parameters were found to be optimal for SR. Accordingly, the parameter of 0.02 mm – 3 s – 0° is the optimum parameter. This is due to the improved surface quality of lower layer height and exposure time, and horizontal printing angles. The significant increase in Sa values as layer height increases is directly related to the layer-by-layer manufacturing process in the mSLA method. Increasing layer thickness increases the height difference between layers, creating a surface structure known as the "stair-step effect," leading to greater surface topography irregularities. The increase in surface roughness, particularly at high printing angles such as 45°, can be explained by the fact that layers' overlap with larger lateral steps in inclined printing. High build angle values are known to increase surface defects, and this study yielded similar results (Goracci et al., 2025). The statistically significant effects of build angle on both as-printed and post-cured samples indicate that surface roughness is highly sensitive to printing direction. 3 s exposure times is also ideal for the mSLA method. A longer exposure time increases roughness due to excessive polymerization of the layers (Pszczółkowski and Zaborowska, 2025).

The ANOVA results in Table 4 statistically determined the parameters that influence surface roughness. Values less than $p < 0.05$ are considered effective in the ANOVA. Accordingly, layer height was determined to be the most effective parameter on SR. The other parameters were relatively less effective. When the contribution percentages were examined, similar to the Taguchi analysis, layer height was the most influential parameter, followed by build angle and exposure time. R^2 (coefficient of determination) is a statistical term that indicates how well the input parameters explain the outputs. For as-printed parts, R^2 was calculated as 0.99. This result demonstrates the high correlation between the outputs and the inputs.

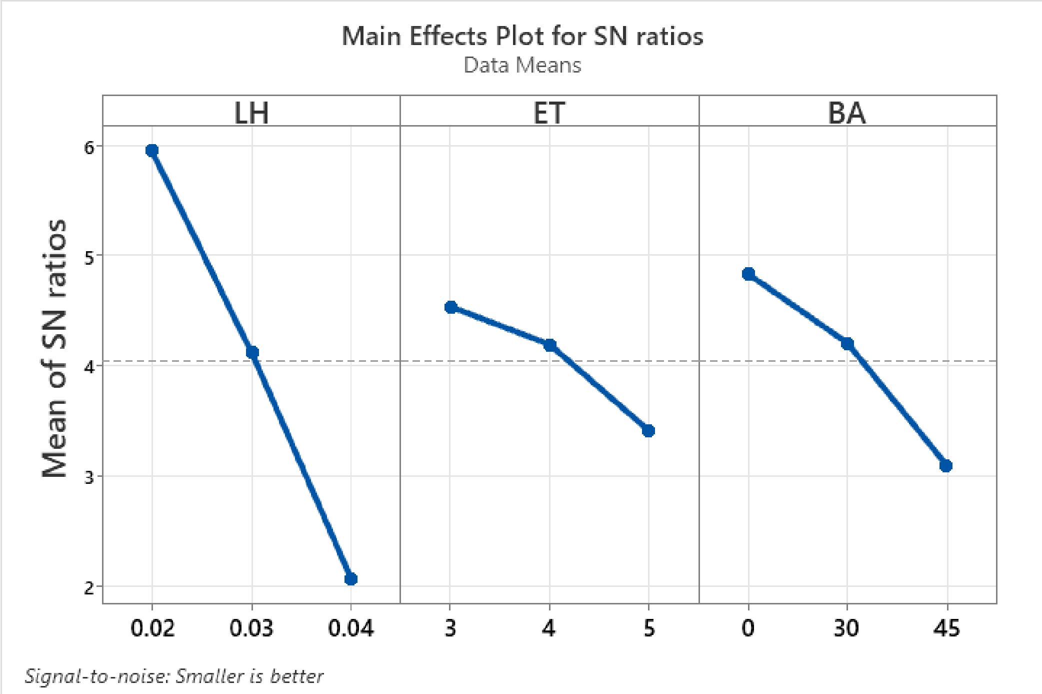

Figure 3. SN ratios for as-printed samples.

Table 4. ANOVA for as-printed samples

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)	P-Value
LH	2	0.117124	0.058562	57.67	80.5	0.017
ET	2	0.007876	0.003938	3.88	5.4	0.205
BA	2	0.020558	0.010279	10.12	14.1	0.090
Error	2	0.002031	0.001015			
Total	8	0.147589				

3.2. SR Analysis of Cured Samples

The Taguchi analysis calculated using the SR results of the post-cured parts is given in Table 5. According to the results in the table, the effects of the parameters on SR are layer height, build angle, and exposure time, respectively. Figure 4 shows the SN ratio plot showing the effective parameter levels. Accordingly, the optimum levels were found to be 0.02 mm – 3 s – 0°, similar to those for as-printed. Significant differences were identified between the surface roughness of the as-printed and post-cured samples. However, the fact that the parameters affecting surface roughness were similar in order of influence for both sample groups suggests that surface roughness is primarily due to the printing parameters. Because the post-curing process proportionally reduced the surface roughness of the cured samples, the optimum levels for surface roughness output were also the same. This suggests that, although post-curing reduced surface roughness, the effects of the printing parameters on the surface characteristics remained unchanged.

Table 5. Taguchi analysis of cured samples

Level	LH	ET	BA
1	6.867	5.435	5.700
2	5.010	5.036	5.087
3	2.899	4.305	3.988
Delta	3.968	1.130	1.712
Rank	1	3	2

The ANOVA results presented in Table 6 determined the effective parameters for the post-cured parts. Since $p < 0.05$ was less than 0.05, layer height was determined to be the most effective parameter on SR. Contribution percentages, similar to Taguchi analysis, determined layer height to be the most effective parameter, followed by build angle and exposure time. R^2 for the post-cured parts was calculated as 0.98. The fact that layer height was the most effective parameter on the post-cured samples does not indicate that curing did not reduce the stair step effect. This is because surface roughness decreased in all post-cured samples. However, although surface roughness decreased in the post-cured samples, high indentations and protrusions on the surface increased roughness. This also led to layer height being effective on the post-cured samples.

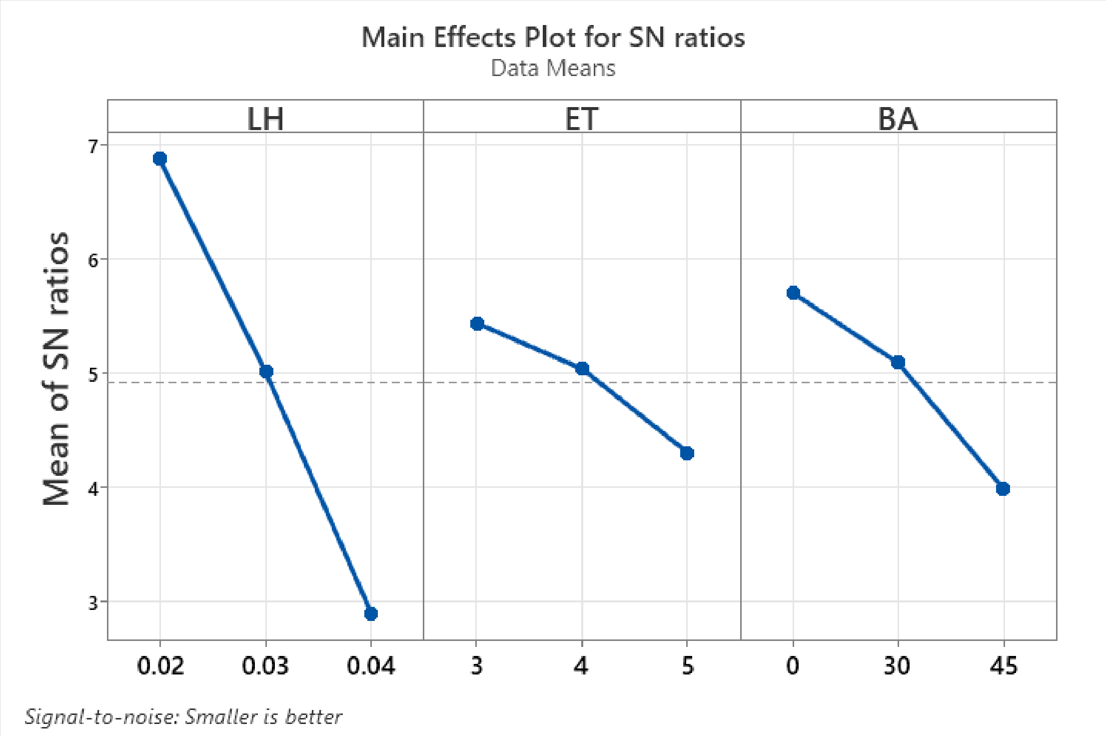

Figure 4. SN ratios for cured samples.

Table 6. ANOVA for post-cured samples

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)	P-Value
LH	2	0.099895	0.049947	37.07	81.8	0.026
ET	2	0.006283	0.003141	2.33	5.2	0.300
BA	2	0.015910	0.007955	5.90	13.0	0.145
Error	2	0.002695	0.001347			
Total	8	0.124783				

3.3. ΔSa Analysis

The Taguchi analysis results for ΔSa are given in Table 7. ΔSa results are similar to the surface roughness analyses. The parameters affecting the layer height, build angle, and exposure time are, respectively. To investigate the effect of curing on surface roughness, the parameters and levels affecting ΔSa were investigated. As seen in the SN ratio plot in Figure 5, the highest level of each parameter has the most impact on ΔSa. Thus, the parameters 0.04 mm, 5 s, and 45° were determined as the optimum parameters for ΔSa. This result demonstrates that the defect removal effect of post-curing is particularly effective in cases with high initial surface irregularities. Due to the high stair step effect, particularly observed at high layer height and build angle values, increased surface roughness was further improved by post-curing. Thus, the effect of post-curing was greater in parts printed with high levels of surface roughness. Consequently, post-curing alone does not provide good surface quality; it is a complementary process whose capacity to improve print defects depends on the initial surface morphology produced by the printing parameters.

Table 7. Taguchi analysis of ΔSa

Level	LH	ET	BA
1	-25.94	-24.70	-25.36
2	-24.40	-24.93	-24.54
3	-22.90	-23.61	-23.34
Delta	3.04	1.32	2.01
Rank	1	3	2

Table 8 shows the ANOVA results for ΔSa, showing the effective parameters and contribution percentages. The effective parameter on ΔSa was determined as layer height. Contribution percentages were found similarly using Taguchi analysis. R^2 for ΔSa was calculated as 0.98, indicating a strong relationship between inputs and outputs. From an application-oriented perspective, these findings clearly demonstrate that the post-curing process should not be interpreted as a corrective process compensating for poorly chosen printing parameters. Instead, post-curing functions as a complementary improvement step whose effectiveness is proportional to the magnitude of the initial surface irregularity. In other words, while rougher surfaces benefit more from post-curing in absolute terms (higher ΔSa), overall surface quality remains primarily governed by the printing parameters. Therefore, achieving high surface performance in mSLA production primarily requires optimizing the printing conditions, while post-curing serves as a secondary improvement step.

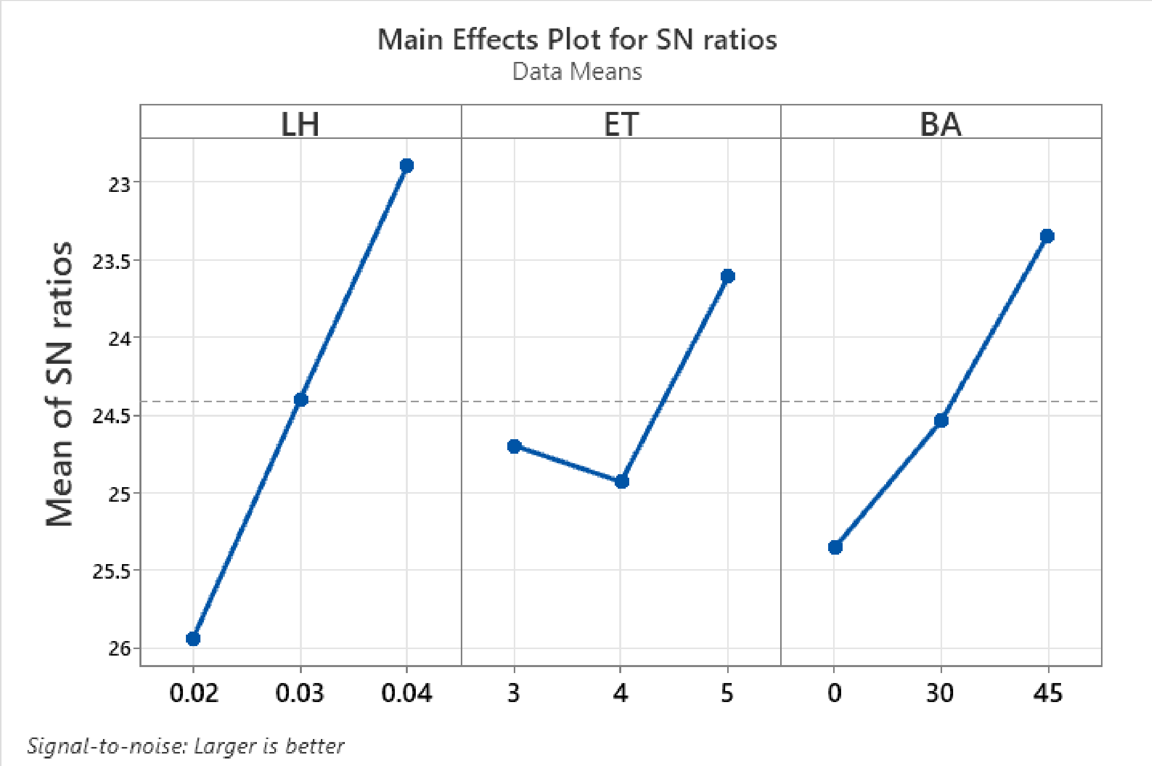

Figure 5. SN ratio plots for ΔSa.

Table 8. ANOVA for ΔSa

Source	DF	Adj SS	Adj MS	F-Value	Contribution (%)	P-Value
LH	2	52.929	26.465	23.93	59.2	0.040
ET	2	12.799	6.399	5.79	14.3	0.147
BA	2	23.726	11.863	10.73	26.5	0.085
Error	2	2.212	1.106			
Total	8	91.665				

4. Conclusion

This study evaluated the effects of printing parameters and post-curing process on the surface roughness of photopolymer-based parts produced using the mSLA method. Experimental data showed that surface quality was significantly affected by both printing parameters and the applied post-curing process. In particular, it was observed that layer thickness played a decisive role in the irregularities formed in the surface topography, while the printing angle increased the direction and intensity of this effect. Exposure time was found to have a more limited effect compared to other parameters.

The post-curing process reduced surface roughness in all experimental combinations, confirming its post-production applicability. However, the magnitude of this improving effect directly depends on the initial surface irregularity; therefore, the post-curing process was found to be more effective in samples with rougher surface morphology. The lowest surface roughness values were obtained with a layer thickness of 0.02 mm, an exposure time of 3 seconds, and a printing angle of 0°. This shows that thin-layered, horizontally oriented prints with short exposure times are more advantageous in terms of improving surface quality.

It was determined that the effect of final curing is not constant, but rather directly related to the initial surface morphology formed during production. ΔSa analyses used in the experiments revealed that the higher the initial surface irregularity, the greater the improvement obtained with post-curing. This shows that the ability of post-curing to smooth the surface depends on the size and distribution of existing surface defects. Parameters such as high layer thickness and printing angle create more of a "staircase" effect during production, and it was determined that such surfaces benefit more from post-curing.

However, this finding does not mean that post-curing is a single process sufficient to optimize surface quality under all conditions. On the contrary, post-curing can correct micro-level irregularities formed during printing to a certain extent, but it is a complementary process that cannot completely eliminate printing-related structural defects. Therefore, in applications requiring high surface quality, approaches such as simply increasing the post-curing duration or changing UV exposure may be insufficient. Accurate definition of printing parameters plays a critical role in optimizing post-curing results.

A limitation of the present study is that post-curing was performed using a single exposure time (15 min) and a single wavelength (405 nm). As a result, the conclusions regarding the proportional improvement in surface roughness are valid only within these curing conditions. Future research should systematically investigate varying curing durations, energy densities, and wavelengths to determine whether the observed proportional relationship between initial surface irregularity and post-curing effectiveness remains consistent under different photopolymerization environments.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	M.A.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because there was no study on animals or humans.

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