EFFECT OF THE PRINTING PARAMETERS ON THE TENSILE STRENGTH AND SURFACE ROUGHNESS OF A PHOTOPOLYMER RESIN USING DLP 3D PRINTING

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Abstract. The advancement of Digital Light Processing (DLP) in 3D printing has catalysed the production of high-quality parts characterized by their high resolution and swift manufacturing turnaround. Despite its popularity, the detailed effects of specific printing parameters on material properties have not been fully outlined. This study investigated how layer height, exposure time, and bottom exposure time influence the tensile strength and surface roughness of photopolymer resin parts produced via DLP. Utilizing a Taguchi method 9v9 experimental design, the contribution of each parameter to the variance in mechanical properties were explored. The statistical analysis reveals that layer height significantly dictates the surface roughness, contributing to 52.97% of the total variance. Simultaneously, bottom exposure time and layer height substantially influence tensile strength, accounting for 29.64% and 19.00% of the variance, respectively. Exposure time, however, has a minimal impact, contributing just 1.36% to tensile strength and showing negligible effects on surface roughness. Optimization efforts identified a layer height of 0.05 mm and bottom exposure time of 15 seconds as optimal, markedly improving tensile strength and surface finish. Scanning electron microscope (SEM) analysis correlates these optimized parameters with crack morphology, offering microstructural evidence that parts printed with optimal settings demonstrate a more resistant structure to tensile forces, as indicated by the presence of rougher, more tortuous crack patterns on stronger samples. The optimal parameters serve as a benchmark for producing parts with superior mechanical strength and surface integrity, thereby fulfilling the increasing industrial demand for robust, 3D-printed components.

Keywords: DLP, layer height, exposure time, tensile strength, surface roughness

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1. INTRODUCTION

Over the past two decades, 3D printing technologies, such as Digital Light Processing (DLP), have experienced a surge in popularity due to their ability to efficiently produce high-resolution components [1]. DLP in which utilizes ultraviolet light to cure photopolymer resins layer by layer, has emerged as a pivotal player in the realm of additive manufacturing (AM) [2]. Despite its advancements, there remains a significant gap in understanding how specific DLP printing parameters that are layer height, exposure time, and bottom exposure time which can affect the mechanical properties and surface quality of the final products [3]. While existing studies have provided valuable insights into DLP technology, many have been limited to comparative analyses between DLP and Stereolithography (SLA) [4]. Furthermore, the interaction between printing parameters and material properties, particularly in relation to tensile strength and surface roughness, has been inadequately explored [5]. Additionally, the challenges in producing thin-wall structures and the detailed effects of parameters on material behaviour have not been comprehensively addressed [6].

This study is motivated by the absence of research on the optimization of printing parameters for enhanced mechanical properties and surface quality. Previous works, [7] have made effort in understanding the effects of print on the tribological and mechanical properties of DLP-printed polymers. However, these studies lack a holistic optimization approach that could mitigate the anisotropic behaviour identified in DLP-printed materials. Study by [8] have suggested that material properties and post-processing techniques play crucial roles in the final outcomes of DLP-printed components. These studies, while invaluable, highlight the existing gap in comprehensive research dedicated to systematically optimizing DLP printing parameters to overcome the current limitations of material performance and surface quality in additive manufacturing.

Prior research has shown that even minor adjustments to these parameters can result in significant differences in part quality [9-10], but a comprehensive understanding of their interrelations and combined effects remains insufficient. This work is novel in its application of a systematic approach, employing the Taguchi method and a 9x9 experimental design array, to not only investigate these effects but also optimize the parameters for improved mechanical performance and surface quality [11]. We discovered that layer height has the most profound impact on surface roughness, while bottom exposure time is a critical determinant of tensile strength. Additionally, SEM analyses linked microstructural characteristics to mechanical behaviour, providing a new layer of insight into material performance [5,12]. The findings of this research are significant, offering actionable guidance for refining DLP printing parameters. They stand to benefit sectors reliant on high-quality 3D-printed parts, like dentistry and jewellery manufacturing, where precision and strength are important. By pinpointing optimal parameter settings, this study enhances the capability to produce components that meet and exceed conventional quality standards, marking a notable contribution to the field of additive manufacturing. This study focusses on analyses of how layer thickness, exposure time, and bottom exposure time influence tensile strength and surface roughness in DLP-printed parts.

2. MATERIALS AND METHODS

The tensile test sample was designed in accordance with ASTM standard D638 type IV design. This design model was used due to the ease of conducting tensile test experiment compared to other design. The design and dimension of the tensile test sample are shown in Figure 1. The material used for the sample production was a photopolymer resin from a Magma_Photopolymer Resin Series 500 g (3D Gadgets). This resin releases a super low odour and produces high detail prints with high hardness. The material density, viscosity, hardness, and tensile strength are approximately 1.15 g/cm^3, 275 MPa.s, 86.5 D, and 44 MPa, respectively.

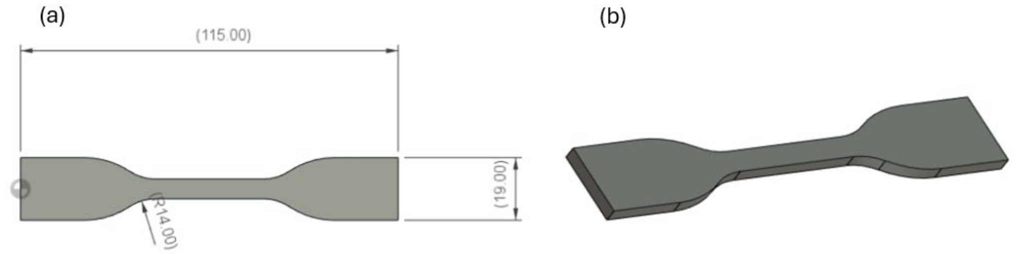

Figure 1: Design of the ASTM D638 type IV sample: (a) dimension of the sample, and (b) isometric view of the sample

2.1 Printer Configuration

Based on Chitubox slicer software, three parameters were manipulated to determine the optimum parameters for the DLP-3D printing process. Three parameters were chosen in this study based on the common controllable DLP printing parameters setting [11,12]. The parameters considered in the study are shown in Table 1. The other printing parameters were set as constants.

Table 1: Printer configuration

Printer material	Photopolymer resin		
Layer height (mm)	0.05	0.10	0.15
Exposure time (s)	3.5	7.0	10.5
Bottom exposure (s)	15	30	60

2.2 Design of Experiment

Three of the printing parameters (layer height, exposure time, and bottom exposure time) are varied based on Taguchi 9v9 array experimental design. The definition of layer height is referred to the thickness of each layer in the z-direction, exposure time is the length of time that each layer will be exposed by the light source during printing, and bottom exposure time refers to the duration chosen for the first few layers. Table 2 shows the printing parameters associated with the Taguchi method.

Table 2: Printing parameters for the design of experiment

No.	Exposure time (s)	Layer height (mm)	Bottom exposure (s)
1	3.5	0.05	15
2	3.5	0.10	30
3	3.5	0.15	60
4	7.0	0.05	30
5	7.0	0.10	60
6	7.0	0.15	15
7	10.5	0.05	60
8	10.5	0.10	15
9	10.5	0.15	30

2.3 Printing and Post-Curing Process

In this work, a Creality LD-006 was used as the DLP 3D printer. This resin 3D printer is a commercial DLP 3D printer in which the photopolymer resin is cured using the UV rays from a profile projector. The XY axis resolution is 0.05 mm, and, in this study, the build orientation is on the Z axis considering that it is easy to remove, and more clean samples can be fabricated. Figure 2(a) shows one of the nine samples that was successfully printed for the experiment. After the printing process, the sample was clean properly to remove any excess uncured resin. The sample then were cured and subjected to tensile tests and surface roughness tests. The sample was exposed to UV light for 15 min using a Fungdo branded UV resin curing light box. Figure 2(b) shows a sample being cured by the UV light.

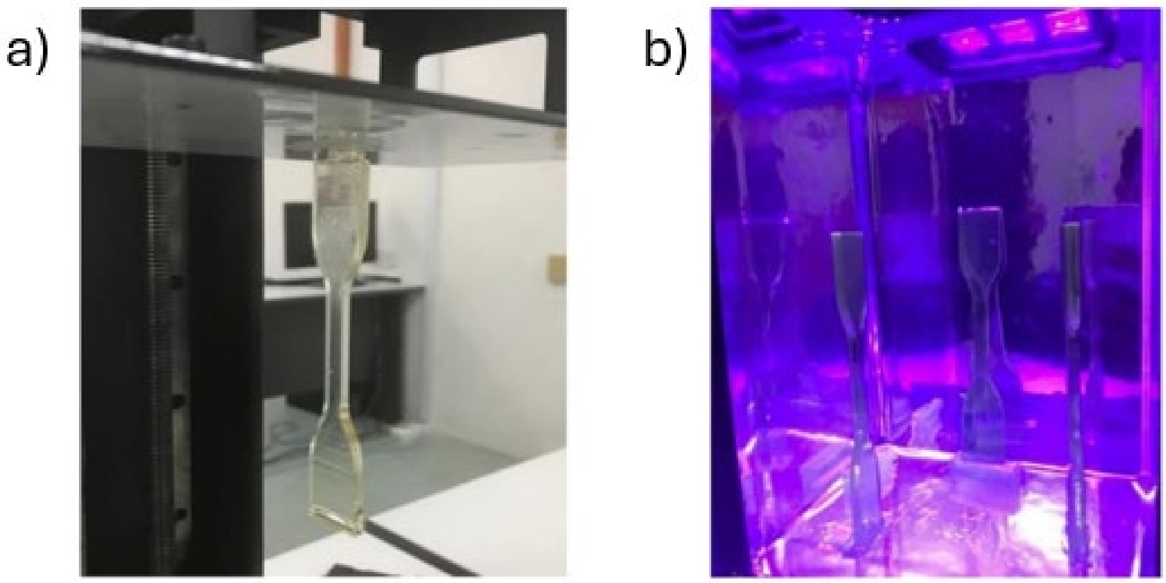

Figure 2: A printed sample (a) before post-curing process, and (b) after the post-curing process

2.4 Tensile and Surface Roughness Testing

The test was performed in accordance with the standard ASTM D638 Tensile Test Methods for polymer using universal testing machine, Shimadzu AGS-X (Shimadzu corporation, Japan). Each specimen underwent elongation at a consistent rate of 50 mm/min with load cell of 5kN to ascertain the force necessary for failure. These tensile tests are crucial for quantifying the material's strength and ductility. The surface roughness measurement was conducted in accordance with the ISO 4287 Surface Roughness Measurement. The sample was placed under an Alicona Infinite Focus SL machine for calculation of the Ra value.

2.5 Scanning Electron Microscope

Preparation for scanning electron microscope (SEM) commenced with the selection of samples that exhibited the highest and lowest tensile strength from the experimental group. Samples were sputter-coated with a conductive layer to enhance electron signal quality and mitigate charging effects during SEM examination. The specimens were then carefully mounted on SEM stubs using a carbon adhesive tape to ensure stable positioning within the imaging chamber. SEM analyses were conducted using an IT 100 SEM system. The instrument was calibrated to optimize resolution and contrast, facilitating the examination of fracture surfaces at magnifications sufficient to discern the crack patterns on the sample. The system’s secondary electron detector was utilized to capture high-resolution images that revealed differences in the crack structure sizes between the samples with the highest and lowest tensile strengths.

3. RESULTS AND DISCUSSION

3.1 Tensile Test

Table 3 shows the effects of layer thickness, exposure time, and bottom exposure time on tensile strength. Although not directly measured in this study, the tensile modulus or Young’s modulus, a key indicator of material stiffness, must be considered when interpreting these results. This modulus, which reflects resistance to elastic deformation, is vital for material selection and engineering design, as it explains variations in load at break; higher loads generally indicate a stiffer material, assuming consistent material properties and cross-sectional areas [13]. The duration to break, which was observed, reflects the material’s ductility and energy absorption capacity before failure. As noted by Kostic et al. [14], measurements of elastic modulus can be unreliable under low forces and minor elongations, potentially influencing these observations. Longer times to break typically suggest a more ductile material that can deform extensively before rupture. In this study, experiment 1 exhibited the highest load at break and a moderate time to break, indicating robust tensile strength and good ductility-traits desirable for durable applications. Conversely, samples with lower loads and shorter elongation at break generally displayed reduced stiffness and strength.

Table 3: Result of the tensile test

Experiment	Load (N)	Elongation break (mm)	Tensile strength (MPa)	Time to break (s)
1	1098.2	3.7	61.0	4.9
2	805.9	3.4	44.8	4.6
3	632.1	4.7	35.1	6.1
4	977.2	3.7	54.3	4.9
5	672.2	4.6	37.4	6.0
6	763.3	4.4	42.4	5.8
7	776.2	5.5	43.6	7.1
8	853.4	2.8	47.4	3.9
9	868.9	5.3	48.3	6.8

Experiment 1 has the highest tensile strength (61.013 MPa) with a time of 4.9 s until the sample breaks and an elongation of 3.7 mm at the breakage point. Experiment 3 has the lowest tensile strength (35.11 MPa) with a time of 6.1 s until the sample breaks (elongation at breakage point: 4.66 mm). A higher degree of resin curing, possibly achieved in experiment 1 due to more optimal printing parameters, could lead to a denser cross-linked network, resulting in higher tensile strength and a stiffer material. Furthermore, a lower degree of cure in experiment 3 might result in a less densely cross-linked network, contributing to greater material ductility and elongation, albeit at a lower tensile strength [15]. Taguchi data analysis was performed on effect of parameters to tensile strength. Subsequently, a regression analysis of tensile strength versus all the parameters was performed to determine which of the three parameters has the greatest impact on the strength. A p-value of <0.05 is statistically significant in most circumstances, and the null hypothesis should be rejected [16]. Table 4 lists the mean values; the bottom exposure is ranked first, followed by the layer height, and then the exposure time. This result indicates which parameters have the greatest influence on the tensile strength value. Moreover, Figure 3(a) and (b) show the main effect plot for the mean values and interaction plot for two significant parameters, respectively. Figure 3(a) and (b) indicate that the decreasing bottom exposure time and layer thickness will increase the tensile strength. It also proved that sample from experiment 1 (Table 2) with the lowest bottom exposure time and lower layer thickness contributes the highest tensile strength with a value of 61.013 MPa while sample from experiment 2 with the highest bottom exposure time and layer thickness contributes the lowest value which is 35.114 MPa. The result has been analysed using analysis of variance (ANOVA) to see whether these results contribute significantly to affecting the tensile strength.

Table 4: Mean values of tensile strength

Level	Exposure Time (s)	Layer Height (mm)	Bottom Exposure (s)
1	454,748	529,817	522,752
2	446,843	436,848	476,257
3	484,372	419,298	386,954
Delta	37,530	110,519	135,798
Rank	3	2	1

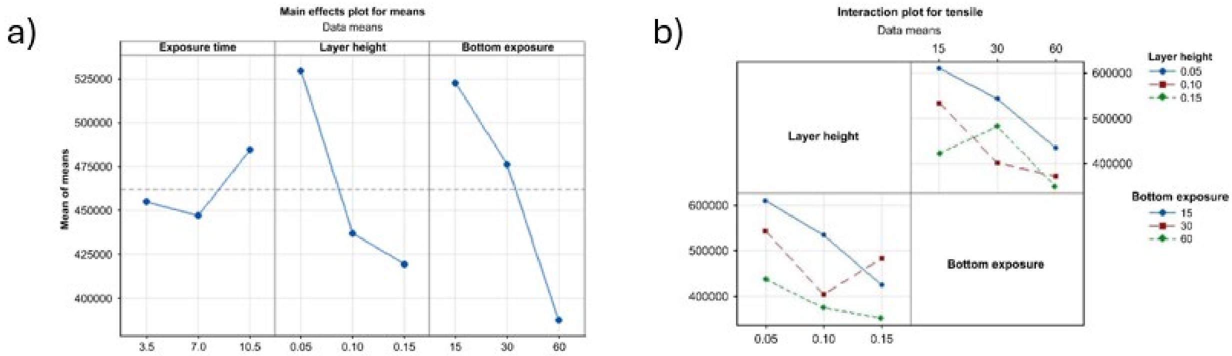

Figure 3: (a) Main effect plot for mean values of tensile strength, and (b) Interaction plot for two significant parameters

The analysis of variance (ANOVA) of the tensile strength (Table 5) reveals a p-value of 0.017 (i.e., <0.05) for the bottom exposure, and therefore, this parameter can be considered significant. The layer height, with a p-value of 0.038 (i.e., <0.05), can also be considered a significant parameter. However, a p-value of 0.486 (i.e., >0.05) for the exposure time indicates that this parameter has no significant effect on the tensile strength. Therefore, the tensile strength is affected by the bottom exposure and the layer height. All the data obtained suggest that the tensile strength of the printing product decreases with increasing bottom exposure time and layer height. The bottom layer is the first layer to expose to the UV light and it is very crucial to ensure the printed parts stick to the build plate firmly. The right amount of time of bottom exposure time is needed to ensure the printing process is successful. Too much exposure to the bottom layer will somehow affect the sample structure. On the other hand, higher layer thickness will contribute lowest tensile strength due to the lower degree of curing for thicker layers and this finding also aligned with the previous study [10].

Table 5: ANOVA of the parameters associated with the tensile strength

Source	DF	F-Value	P-Value
Regression	3	6.90	0.032
Exposure time	1	0.57	0.486
Layer height	1	7.87	0.038
Bottom exposure	1	12.27	0.017
Error	5		
Total	8		

3.2 Analysis of the Surface Roughness

Table 6 shows the mean roughness values obtained, and Figure 4 shows the graph for the main effect plot of these values. As shown in the table, the layer height is ranked first, followed by the exposure time, and then the bottom exposure. This result shows the parameters that exert the greatest influence on the Ra value of the printed product.

Table 6: Mean values of surface roughness

Level	Exposure time (s)	Layer height (mm)	Bottom exposure (s)
1	6.5	3.2	6.5
2	6.6	5.0	4.2
3	3.7	8.7	6.1
Delta	3.0	5.5	2.3
Rank	2	1	3

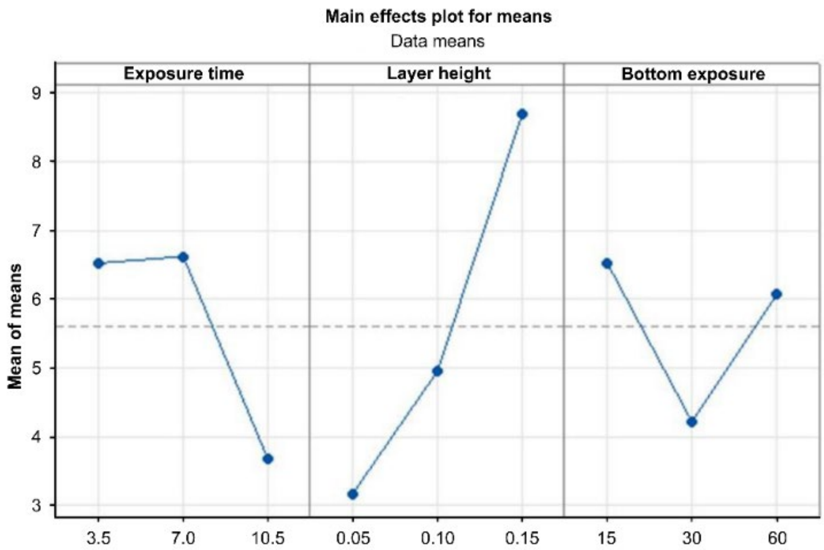

Figure 4: Graph for main effects plot of the means obtained for the surface roughness

The ANOVA of surface roughness, detailed in Table 7, shows that bottom exposure and exposure time have p-values greater than 0.05, indicating no significant effect on surface roughness. However, the p-value for layer height is 0.036, which is less than 0.05, suggesting a significant impact on roughness. This effect is likely due to the thickness of the cured resin; thicker layers receive less UV light penetration, resulting in a more uneven surface and a higher Ra value. Thus, layer height directly correlates with the surface roughness of the printed product.

Table 7: ANOVA of the parameters associated with the surface roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	58.0070	19.3357	3.40	0.111
Exposure time	1	12.2056	12.2056	2.14	0.203
Layer height	1	45.8013	45.8013	8.05	0.036
Bottom exposure	1	0.0001	0.0001	0.00	0.997
Error	5	28.4545	5.6909		
Total	8	86.4615			

3.3 Optimum Parameters

From the experimental result, the optimum parameters obtained for the optimum tensile strength are 15 s of bottom exposure time and 0.05 mm of layer height. The results indicate that low layer heights and long bottom exposure times contribute to high tensile strength. Regarding the surface roughness of the printed product, a layer height of 0.05 mm yields the smoothest surface. The results suggest that, compared with larger heights, smaller layer heights yield a smoother surface of the printed product.

3.4 Fracture Morphology

Scanning electron microscopy was used to observe the crack structures on the neck of samples with varying tensile strengths. Figure 5 displays the crack morphology for Samples 1, 7, and 3 at magnifications of x50 and x100.

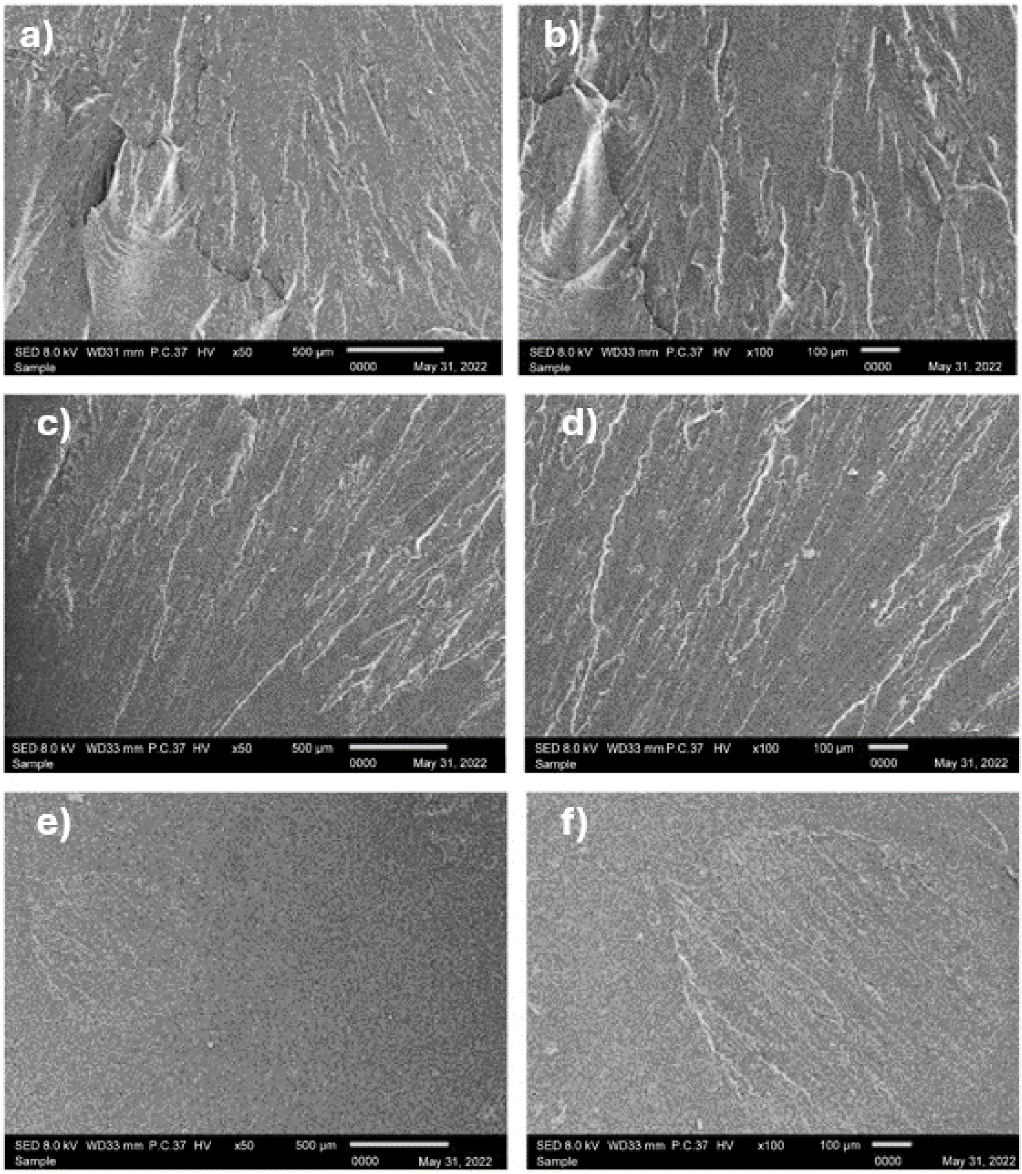

Figure 5: SEM micrographs showing the crack structure. (a) and (b) represent sample 1, (c) and (d) represent sample 3, and (e) and (f) represent sample 7

Sample 1, with the highest tensile strength, shows a rough and coarse cracking structure (Figure 5(a) and (b)), indicative of high resistance to crack initiation and propagation. This suggests a tortuous crack path and higher energy dissipation during crack growth. In contrast, Sample 7 shows a smoother cracking structure (Figure 5(c) and (d)), while Sample 3, the weakest, displays a smooth surface with minor cracks (Figure 5(e) and (f)), suggesting a lower energy barrier to crack growth and a straightforward crack path. These observations correlate with theoretical studies on crack propagation and material strength. For instance, Li et al. [17] discuss how crack propagation behaviour is influenced by the interaction between cleavage fracture and void growth, with rougher crack morphologies associated with higher tensile strength due to increased resistance to crack growth. Similarly, Liu et al. [18] explain that shallow cracks can enhance tensile strength by promoting strain hardening around the crack tip due to redistributed strain, supporting the observed higher strength in samples with coarser cracks.

4. CONCLUSIONS

Using the Taguchi method, this study assessed how layer height, exposure time, and bottom exposure time influence tensile strength and surface roughness of DLP-printed products. We discovered that both layer height and bottom exposure time significantly affect tensile strength, with increased layer height and exposure time leading to decreased strength. In terms of surface roughness, layer height was the sole influential parameter, increasing roughness as it increased. SEM analysis further revealed that samples with higher tensile strength exhibited rough and coarse cracking structures, suggesting a more complex and energy-absorbing crack path that enhances resistance to crack initiation and propagation. Conversely, samples with lower tensile strength displayed smoother crack surfaces, indicating a simpler path for crack propagation. The optimal printing parameters identified were a bottom exposure time of 15 seconds and a layer height of 0.05 mm, which also resulted in the lowest surface roughness. These findings provide actionable insights for improving the fabrication quality of 3D-printed products using photopolymer resins. This research not only advances the additive manufacturing process but also supports the use of photopolymer resin materials in final products and prototypes across various industries, including jewellery, low-run injection moulding, and dental and medical applications. Future studies can build on these results, potentially enhancing both academic research and practical applications in numerous industrial sectors.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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