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OPTIMIZATION OF PROCESS PARAMETERS AND POST-PROCESSING OF SLA 3D PRINTING ON THE HARDNESS OF PHOTOPOLYMER RESIN USING THE TAGUCHI METHOD

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ABSTRACT

The limited availability of plastic components for classic automotive vehicles has encouraged the utilization of stereolithography (SLA) 3D printing technology as an alternative manufacturing method. However, studies regarding the optimization of SLA printing and post-processing parameters on the hardness characteristics of photopolymer resin are still limited. This study aimed to optimize SLA process and post-process parameters to improve resin hardness. The investigated parameters were layer thickness, exposure time, washing time, and curing time. The experimental design employed the Taguchi method with an L9 (3^4) orthogonal array. Specimens were fabricated using an Anycubic Photon Mono 2 printer ABS-Like Resin Pro 2 material, followed by washing and curing processes according to experimental parameters. Hardness testing was conducted using the Shore D method based on ASTM D2240 standards. The experimental data were analyzed using signal-to-noise (S/N) ratio analysis, analysis of variance (ANOVA), and percentage contribution analysis with Minitab software. The results indicated that layer thickness exhibited the highest contribution ratio (47.24%), followed by exposure time (34.62%) and washing time (14.21%). However, ANOVA results indicated none of the investigated factors were statistically significant at the 95% confidence level ($p > 0.05$). The optimal parameter combination consisted of 0.20 mm layer thickness, 9 s exposure time, 5 min washing time, and 20 min curing time. Confirmation experiments produced a hardness value of 87.8 Shore D, which was close to the predicted value of 88.0333 Shore D. These findings demonstrate that Taguchi method is effective for determining optimal SLA printing parameters to enhance photopolymer resin hardness.

Keywords: 3D Printing, Stereolithography, Photopolymer Resin, Hardness, Taguchi Method

INTRODUCTION

In the automotive industry, the limited availability of components for classic vehicles has become an increasingly significant issue, particularly for plastic-based components. Classic vehicles are still widely used and favored in Indonesia due to their historical value and unique characteristics for enthusiast communities and collectors. The interest in classic motorcycles in Indonesia continues to increase; however, the availability of classic motorcycle spare parts, both replacement parts and accessories, is relatively difficult to obtain, whether original or non-original [1]. This condition makes it difficult for vehicle owners to carry out maintenance and repairs, especially for non-structural components that support the functionality and aesthetics of the vehicle.

One solution that can be applied to overcome this problem is the use of additive manufacturing (AM) technology. This technology has an increasingly important role in reproducing automotive spare parts that are no longer available on the market, particularly for classic vehicles [2]. Among the various additive manufacturing methods, stereolithography (SLA) was selected because it is capable of producing components with good dimensional accuracy and surface quality. The SLA process produces three-dimensional objects through the selective curing of liquid resin caused by a polymerization reaction triggered by exposure to light energy [3]. In addition, this method is capable of producing smoother surface quality compared to other methods such as fused deposition modeling (FDM) [4], and can manufacture complex geometries with low surface roughness levels [5].

The quality of printed products in the SLA process is highly influenced by the process and post-process parameters used. Process parameters such as layer thickness and exposure time play a role in determining the level of polymerization and dimensional accuracy of the printed products [6]. Meanwhile, post-process parameters such as washing time and post-curing time affect the refinement of the material structure and the stability of mechanical properties [7], [8]. Therefore, proper parameter settings are an important factor in obtaining optimal print quality. One of the mechanical properties used as an indicator of print quality is hardness. Hardness indicates the ability of a material to resist local plastic deformation due to loading on the surface [9, 10]. Hardness testing in this study was conducted using the Shore D method based on the ASTM D2240 standard, which is commonly used for polymer and photopolymer resin materials [11]. Hardness was selected as the primary performance indicator because many plastic components in classic vehicles are subjected to surface contact, friction, scratching, and localized loading during service. Adequate hardness is required to maintain wear resistance, dimensional stability, and surface durability, thereby ensuring the functionality and aesthetic quality of replacement components. These characteristics are particularly important for non-structural automotive parts that are frequently exposed to handling, friction, scratching, and environmental conditions during service. High hardness values are expected to improve the durability and quality of printed components, making them more feasible for use as alternative spare parts for classic automotive vehicles.

Although previous studies have investigated the effects of SLA printing parameters on mechanical properties such as tensile strength, dimensional accuracy, surface quality, and hardness, most studies have focused on either process parameters or post-processing parameters separately. Furthermore, limited studies have evaluated the combined optimization of layer thickness, exposure time, washing time, and curing time on the hardness characteristics of photopolymer resin using the Taguchi method, particularly in desktop SLA systems intended for replacement automotive components. In addition, studies employing the Anycubic Photon Mono 2 printer and ABS-Like Resin Pro 2 material for hardness optimization remain scarce. Therefore, a research gap exists in identifying the optimal combination of process and post-process parameters to improve the hardness performance of SLA-printed photopolymer resin. The novelty of this study lies in the simultaneous optimization of SLA printing and post-processing parameters, namely layer thickness, exposure time, washing time, and curing time, on the hardness characteristics of ABS-Like Resin Pro 2 using the Taguchi L9 orthogonal array design. Unlike previous studies that generally focused on individual process parameters or post-processing conditions, this study evaluates the combined effects of both parameter groups within a single experimental framework using a desktop SLA system. This approach provides a more comprehensive understanding of the interaction between process and post-process parameters affecting the hardness performance of photopolymer resin. Therefore, this study aims to optimize the combination of layer thickness, exposure time, washing time, and curing time to improve the hardness characteristics of photopolymer resin fabricated using SLA technology through the

Taguchi method. This method was selected because it is capable of determining the optimal parameter combination efficiently and analyzing the influence of each factor through the signal-to-noise (S/N) ratio and analysis of variance (ANOVA) [12]. The results of this study are expected to provide recommendations for optimal parameters to improve print quality, particularly in the application of manufacturing plastic components for classic automotive vehicles.

METHOD

1. Research Methodology Workflow

The research stages were carried out systematically to obtain the optimal combination of process and post-process parameters on the hardness value of photopolymer resin produced by SLA 3D printing. The research process began with a literature review, determination of research parameters and levels, experimental design using the Taguchi method, specimen printing process, hardness testing, followed by data analysis and confirmation experiments. The research flowchart is shown in Figure 1.

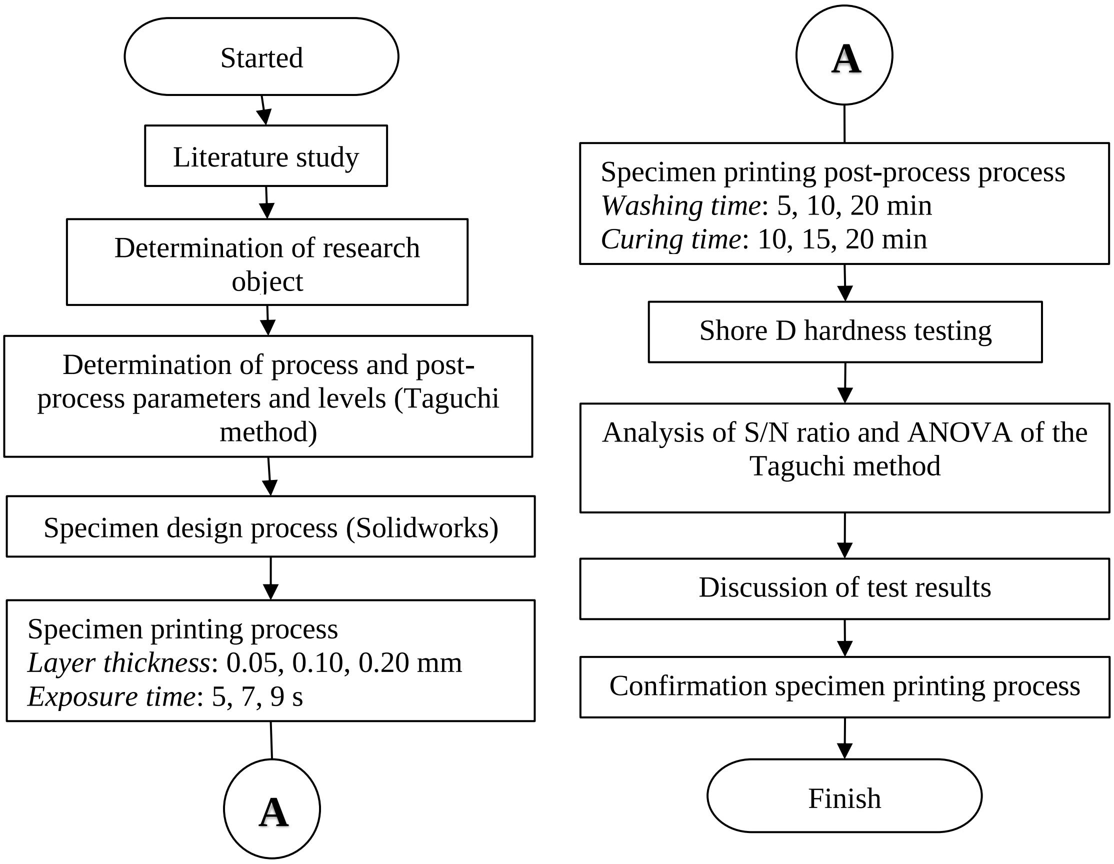

Figure 1. Research Methodology Workflow

2. Design Of Experiments

The determination of research parameters and levels was carried out to identify the influence of each process and post-process parameter on the hardness characteristics of photopolymer resin produced by SLA 3D printing. The research parameters used consisted of layer thickness, exposure time, washing time, and curing time, with each parameter having three variation levels. The selected factor levels were determined based on the processing recommendations provided by the manufacturer of ABS-Like Resin Pro 2, the operating capabilities of the Anycubic Photon Mono 2 printer, and findings from previous studies on SLA process optimization. The layer thickness levels of 0.05 mm, 0.10 mm, and 0.20 mm were selected to represent fine, medium, and coarse printing resolutions commonly used in desktop SLA systems. Meanwhile, the exposure time, washing time, and curing time levels were chosen within practical processing ranges to ensure proper resin polymerization and post-processing while allowing the effects of parameter variation on hardness characteristics to be evaluated. The research parameters and levels are shown in Table 1.

Table 1. Research Parameters and Their Levels

Control Factors	Variasi		
	Level 1	**Level 2**	**Level 3**
Layer Thickness	0,05 mm	0,10 mm	0,20 mm
Exposure Time	5 s	7 s	9 s
Washing Time	5 min	10 min	20 min
Curing Time	10 min	15 min	20 min

Based on the number of parameters and levels used, the experimental design was conducted using the Taguchi method with an L9 (3^4) orthogonal array. The orthogonal array was used to determine the experimental parameter combinations efficiently, thereby reducing the number of experiments without decreasing the quality of the research analysis. The experimental parameter combinations based on the L9 orthogonal array are shown in Table 2.

Table 2. L9 (3^4) Orthogonal Array experimental design

Eksperimen	Layer Thickness (mm)	Exposure Time (s)	Washing Time (min)	Curing Time (min)
1	0,05	5	5	10
2	0,05	7	10	15
3	0,05	9	20	20
4	0,10	5	10	20
5	0,10	7	20	10
6	0,10	9	5	15
7	0,20	5	20	15
8	0,20	7	5	20
9	0,20	9	10	10

The parameter combinations in the L9 orthogonal array were used as a reference in conducting the experiments to determine the influence of process and post-process parameters on the hardness value of photopolymer resin produced by SLA 3D printing.

3. Materials and Equipment

This study used the Anycubic Photon Mono 2 SLA machine and the Anycubic Wash & Cure 2.0 post-processing device. The equipment used in this study included an SLA 3D printing machine, washing and curing machines, and a Shore D Durometer hardness testing device. The specimen washing process was carried out using 99% isopropyl alcohol (IPA) to remove residual uncured resin before the post-curing stage. The material used was Anycubic ABS-Like Resin Pro 2, with the resin material composition presented in Table 3.

Table 3. Material Composition of Anycubic ABS-Like Pro 2 [13]

Feature	Value
UV wavelength	365-405 nm
Viscosity	300-400 mPa.s(25°C)
Density	1.05-1.25 g/cm^3
Hardness	82-84 HD
Tensile strength	35-40 MPa
Elongation at break	35-40 %
Bending modulus	40-45 MPa
Bending strength	1400-1800 MPa
Young's modulus	1600-1800 MPa
Volume Shrinkage Rate	4.3-5.6 %
Izod Impact Strength	212 J/m

The research process began with determining the parameters and levels, followed by the preparation of the experimental design based on the L9 orthogonal array matrix. Furthermore, a three-dimensional specimen was designed using SolidWorks 2021 software operated on a laptop. The completed specimen design was then exported into STL format and imported into the Anycubic Photon Workshop application. In this application, the printing parameters were adjusted according to the combinations specified in the experimental design. The configured parameter data were then applied to the Anycubic Photon Mono 2 machine for specimen fabrication, while the display of parameter settings in the Anycubic Photon Workshop application is shown in Figure 2. To minimize the influence of confounding variables, all specimens were printed using the same printing configuration throughout the experiment. The specimens were fabricated with a 0° print orientation relative to the build platform, identical support structure settings, and a consistent build direction for all experimental runs. These parameters were maintained constant to ensure that variations in hardness were primarily attributed to the investigated process and post-processing parameters.

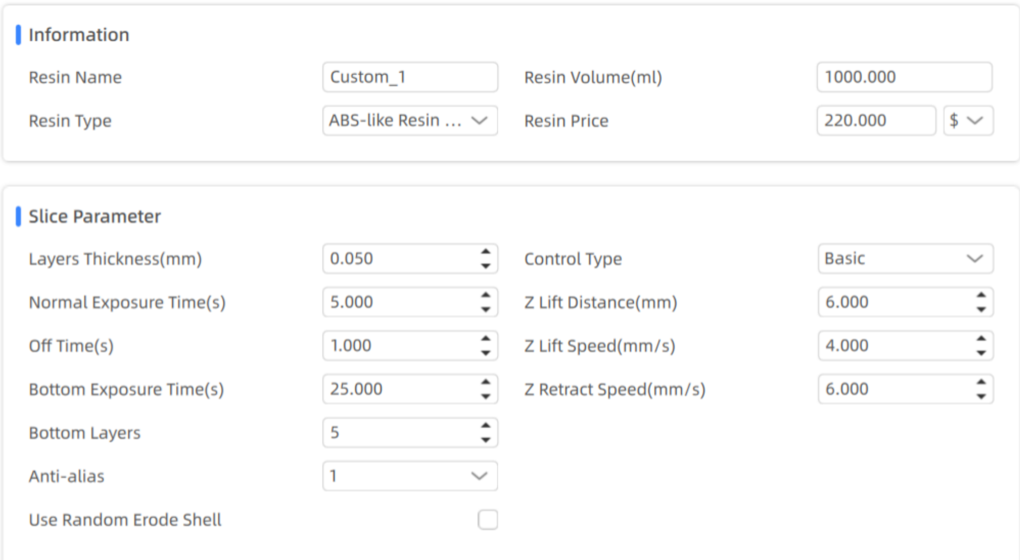

Figure 2. Parameter Settings on Anycubic Workshop Software

The determined parameter data were then saved and exported from the Anycubic Photon Workshop application to a storage device in the form of a flash drive, and subsequently transferred to the Anycubic Photon Mono 2 machine for the specimen printing process. After the printing process was completed, the printed specimens underwent a washing process using 99% isopropyl alcohol (IPA) according to the predetermined washing time variations to remove residual uncured resin using the Anycubic Wash & Cure 2.0 machine. After the washing process, the specimens proceeded to the post-curing stage using the Anycubic Wash & Cure 2.0 machine, with the curing time adjusted based on the research parameters. The printing process and post-processing stages of the specimens are shown in Figure 3.

Figure 3. Printing and Post-Printing Process

After the post-printing process was completed, the test specimens were marked at five points according to the predetermined testing layout. The marked specimens were then subjected to hardness testing using a Shore D Durometer at the five points for each test specimen. The test result data were subsequently processed using Minitab software operated on a laptop. The analysis was conducted through the calculation of the signal-to-noise (S/N) ratio with the larger-is-better characteristic to determine the parameters that produced the highest hardness value, as well as analysis of variance (ANOVA) to identify the level of influence of each parameter on the observed response. Furthermore, the Taguchi prediction calculation was performed using Minitab software to determine the predicted hardness value at the optimal parameter combination based on the results of the S/N ratio analysis.

4. Hardness Testing

The test specimens in this study were designed based on the ASTM D2240 standard as a reference for material hardness testing. The specimen design was created using SolidWorks 2021 software with dimensions of 65 mm × 25 mm × 6 mm. The shape of the specimens to be tested for hardness properties is shown in Figure 4.

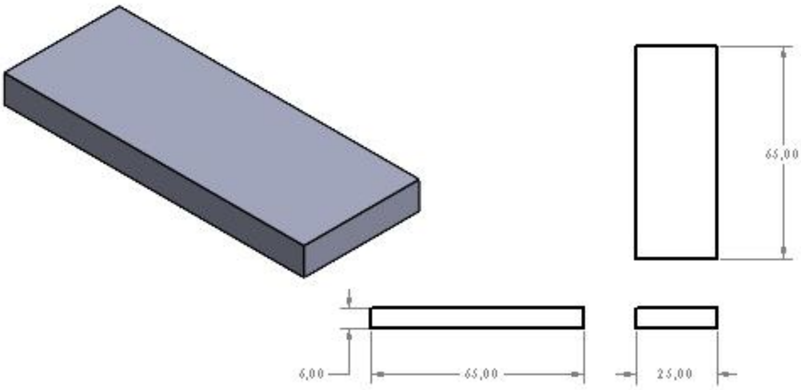

Figure 4. Hardness Test Specimen Design

Hardness measurements were conducted using a Digital Shore D Durometer integrated with the spindle of a drilling machine to ensure the application of uniform pressure. The testing was carried out under laboratory conditions at ambient temperature. For each specimen, hardness data were recorded at five different locations, with the distance between the testing points and the edge of the specimen set at 12.5 mm, while the distance between testing points was 10 mm. During the testing procedure, the specimen was positioned perpendicular to the indenter. The drilling machine lever was then operated to lower the indenter until it contacted the material surface after ensuring full contact between the pressure foot and the specimen surface, thereby obtaining accurate and consistent hardness values. To clarify the measurement positions, the schematic of hardness testing points on each specimen is presented in Figure 5.

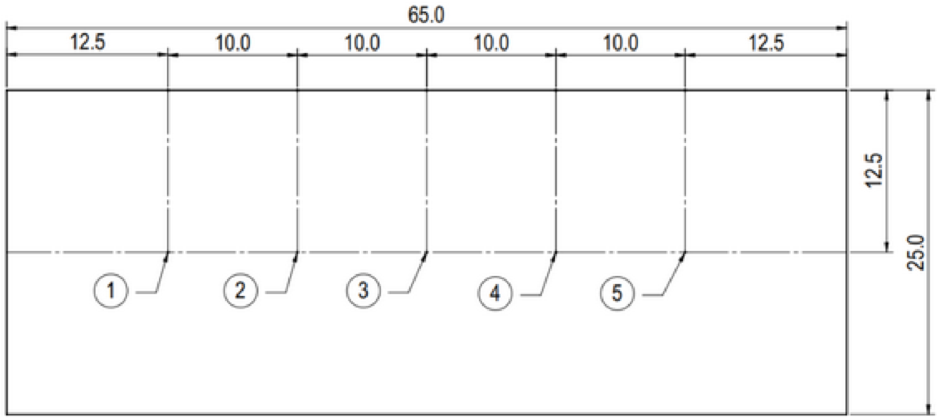

Figure 5. Measurement Point Scheme on ASTM D2240 Hardness Test Specimen

5. Data Analysis

Data analysis in this study was conducted using the Taguchi method to evaluate the influence of process parameters on the material hardness value and to determine the optimal parameter combination. All data processing in this study was carried out using Minitab software operated on a laptop to support statistical calculations. The stages of data analysis were performed systematically through several steps, namely Signal-to-Noise (S/N) ratio calculation, Taguchi prediction, analysis of variance (ANOVA), confirmation testing, and conclusion drawing, as follows:

1. The first stage involved calculating the Signal-to-Noise (S/N) ratio based on the hardness measurement results of each specimen. Signal-to-noise (S/N) ratio analysis was conducted to evaluate the influence of parameter variations on the hardness response, identify factors contributing to the reduction of variation, and determine the factor levels that provided the most optimal experimental results (Book source). The S/N ratio consists of several quality characteristics, namely nominal is best, larger is better, and smaller is better. In this study, the larger-is-better characteristic was used because the objective was to obtain the maximum hardness value. Therefore, the S/N ratio calculation in this study used the larger-is-better characteristic with the following equation:

$$S/N = -10\,log\left(\frac{1}{n}\sum_{i=1}^{r}\frac{1}{y_1^2}\right)$$

2. Furthermore, Taguchi analysis was conducted to predict the hardness value based on the combination of process parameter levels with the optimal Signal-to-Noise (S/N) ratio using Minitab software. The results of this stage were used to obtain the predicted hardness value under optimum conditions.
3. The next stage was analysis of variance (ANOVA), which was used to determine the significance level of the influence of each process parameter on the material hardness value. Analysis of variance (ANOVA) is a statistical method used to analyze data obtained

from experimental design and to determine the magnitude of the influence and contribution of each factor to the observed response. In addition, analysis of variance was also used to identify factors that significantly affected the response. The hypotheses used were as follows:

- Null Hypothesis (H_0): There is no effect of the treatment.
- Alternative Hypothesis (H_1): There is an effect of the treatment.

The testing decision was made based on the criterion that H_0 is rejected if the P-value < 0.05, indicating that the factor has a significant effect on the response [14].

4. After that, a confirmation test was conducted to verify the Taguchi prediction results. This test aimed to compare the experimental hardness value with the predicted value under optimum conditions in order to determine the level of model accuracy.
5. The final stage was drawing conclusions based on the analysis results that had been conducted, which included the influence of process parameters, the optimum parameter combination, and the validation results.

RESULT AND DISCUSSION

The results of this study are presented based on data processing using the Taguchi method, which includes Signal-to-Noise (S/N) ratio analysis, optimum condition prediction, analysis of variance (ANOVA), and confirmation testing. The discussion was conducted to explain the influence of each process parameter on the material hardness value.

1. Hardness Testing Results

Hardness testing was conducted on each test specimen using the Shore D method in accordance with ASTM D2240 with five testing points. The hardness testing process using the Shore D Durometer is shown in Figure 6, while the hardness testing results based on the parameter combinations in the Taguchi experimental design are presented in Table 4.

Figure 6. Specimen Hardness Measurement Using Shore D Durometer

Table 4. Hardness Testing Results of the Specimens

Eksperimen	Points 1	Points 2	Points 3	Points 4	Points 5	Average
1	79,5	80	79,5	83	84	81,2
2	81,5	81	81	82	82	81,5
3	83,5	83	82	82	82	82,5
4	82	83	82,5	85	84,5	83,4
5	84	85	83,5	83	82	83,5
6	86	87	85,5	87	85	86,1

7	82	81,5	82	82	82	81,9
8	86,5	86,5	86,5	87,5	86	86,6
9	87	87	87	87	88,5	87,3

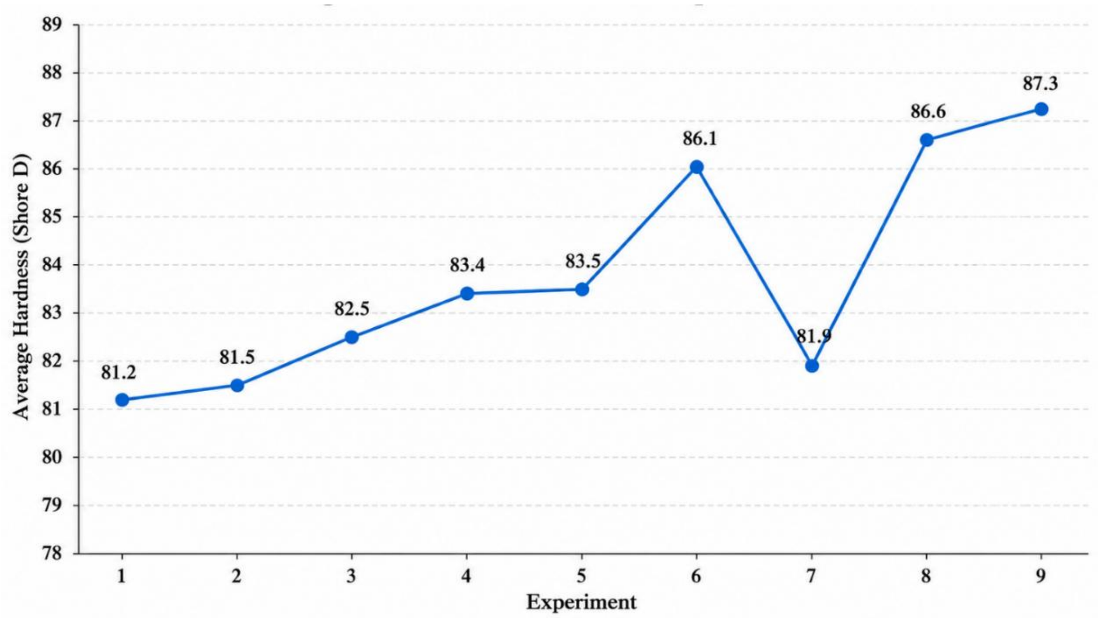

Figure 7. Average Hardness Values Obtained from Each Experimental Run

Figure 7 presents the average hardness values obtained from each experimental run. The hardness values ranged from 81.2 to 87.3 Shore D. The lowest hardness value was observed in Experiment 1, while the highest hardness value was obtained in Experiment 9. These results indicate that variations in process and post-processing parameters influenced the hardness characteristics of the printed photopolymer resin specimens. An overall increasing trend in hardness can be observed across several experimental runs, suggesting that appropriate parameter combinations contributed to enhanced resin polymerization and improved surface hardness.

2. Signal-to-Noise (S/N) Ratio

The Signal-to-Noise (S/N) ratio calculation results were obtained based on the hardness data of each specimen using Minitab software. In this study, the larger-is-better characteristic was used because higher hardness values were desired. This calculation was used to evaluate the hardness response characteristics by considering data variation in each combination of process parameters. The results of the mean and S/N ratio calculations for each experiment are presented in Table 5.

Table 5. Hasil S/N Ratio dan Mean

Eksperimen	Mean	S/N Ratio
1	81,2	38,18399
2	81,5	38,22276
3	82,5	38,32832
4	83,4	38,42082
5	83,5	38,43186
6	86,1	38,69894
7	81,9	38,26560
8	86,6	38,74994
9	87,3	38,81968

Based on Table 4.2, it can be observed that each parameter combination produced different S/N ratio values. The highest S/N ratio value was obtained in experiment 9 at 38.81968 dB, while the lowest value was obtained in experiment 1 at 38.18399 dB. The greater the S/N ratio value, the better the quality and stability of the resulting hardness response. The results of the S/N value calculations for each factor are presented in Table 6.

Table 6. S/N Rasio Larger Is Better

Level	Layer thickness	Exposure time	Washing time	Curing time
1	38,25	38,29	38,54	38,48
2	38,52	38,47	38,49	38,40
3	38,61	38,62	38,34	38,50
Delta	0,37	0,32	0,20	0,10
Rank	1	2	3	4

These results indicate that the layer thickness factor was the most influential factor on the hardness value, followed by exposure time, washing time, and curing time. The greater the delta value obtained, the greater the influence of the factor on the response. To clarify the influence of each factor on the S/N ratio value, a visualization in the form of a main effects plot graph was created based on data processing using Minitab. This graph shows the relationship between each factor level and the S/N value, so that it can be used to identify the response trend changes and determine the parameter levels that provide optimum results. The Main Effects Plot for the S/N ratio is presented in Figure 7.

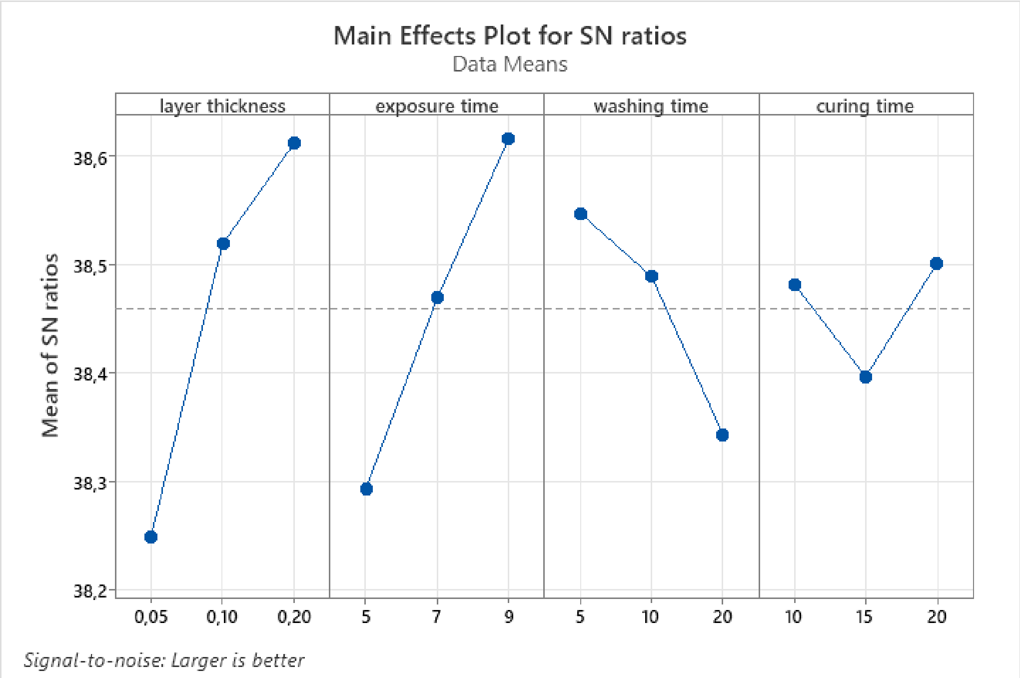

Figure 8. Main Effects Plot S/N Ratio

Based on the S/N ratio main effects plot shown in Figure 8, the highest S/N ratio for layer thickness was obtained at 0.20 mm, indicating that this level provided the most favorable hardness response among the investigated levels. Similarly, exposure time reached its highest S/N ratio at 9 s, suggesting that longer light exposure promoted a higher degree of resin polymerization. For washing time, the highest S/N ratio was observed at 5 min, while curing time achieved its highest value at 20 min. These results indicate that the combination of 0.20 mm layer thickness, 9 s exposure time, 5 min washing time, and 20 min curing time provided the most favorable hardness response based on the S/N ratio analysis.

3. Determination of Optimal Parameters

The determination of the optimum parameters was carried out based on the results of the Signal-to-Noise (S/N) ratio analysis and mean values obtained from data processing using Minitab software. The optimum parameters were determined by selecting the factor levels that produced the highest S/N values, since the larger-is-better characteristic was used in this study. Based on the analysis results, the optimum parameter combination obtained is shown in Table 7.

Table 7. Optimum Parameters

Parameter	Level	Value
Layer thickness	3	0,20 mm
Exposure time	3	9 s
Washing time	1	5 min
Curing time	3	20 min

The combination indicates that the maximum hardness value was obtained under conditions of the largest layer thickness, longer exposure time, shorter washing time, and relatively longer post-curing time. The determination of these optimum parameters was based on the highest S/N value, which indicates conditions with low variation levels and optimal response performance.

4. Prediction of Optimum Parameters

The determination of the optimal parameters was carried out based on the highest Signal-to-Noise (S/N) ratio value for each factor using Minitab software. The mean value was used as a supporting parameter in determining the best level combination. Based on the analysis results, the optimal parameter combination obtained is presented in Table 8.

Table 8. Prediction of Optimum Parameters

Layer thickness	Exposure time	Washing time	Curing time	Hardness	S/N Ratio
0,20 mm	9 s	5 min	20 min	88,0333	38,8974

Based on the Taguchi method prediction results, the parameter combination was predicted to produce an optimum hardness value of 88.0333.

5. Analisis Variansi (ANOVA)

Analysis of variance (ANOVA) was conducted to determine the significance level of the influence of each factor on the material hardness value. Data processing was carried out using Minitab software, with the analyzed parameters including sum of squares (SS), mean square (MS), F-value, p-value, and contribution. The ANOVA results are presented in Table 9.

Table 9. Analysis of Variance (ANOVA)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer thickness	2	0,2175	47,24%	0,2175	0,108751	12,02	0,077
Exposure time	2	0,1594	34,62%	0,1594	0,0797	8,81	0,102
Washing time	2	0,06541	14,21%	0,06541	0,032707	3,61	0,217
Error	2	0,0181	3,93%	0,0181	0,009048		
Total	8	0,46041	100,00%				

Based on the analysis results in Table 9, it was found that the layer thickness parameter had the largest contribution to the hardness value at 47.24%, followed by exposure time at 34.62%, and washing time at 14.21%, while the error contribution was 3.93%. This indicates that layer thickness was the most dominant factor affecting the hardness of the photopolymer resin. However, all parameters had p-values greater than 0.05, namely 0.077 for layer thickness, 0.102 for exposure time, and 0.217 for washing time. indicating that at a 95% confidence level, none of the factors were statistically significant. Therefore, the discussion is based on relative contribution rather than hypothesis testing. In the modeling process using Minitab, the forward selection of terms method was applied with an α to enter value of 0.5. This value was used because, in the initial test with $\alpha = 0.05$, no parameters met the significance criteria, resulting in the inability to establish the model. Therefore, the α value was relaxed so that all factors could be analyzed within the model, particularly to observe the relative contribution of each parameter in accordance with the Taguchi method approach, which focuses on optimization. In addition, the ANOVA table shows that not all parameters were displayed separately, where the curing time parameter did not appear in the table. This was caused by the limitation of degrees of freedom in the Taguchi L9 (3^4) experimental design. In this design, the total degrees of freedom were 8, while the four factors each had 2 degrees of freedom, leaving no degrees of freedom available for error. To overcome this limitation, a pooling technique was applied.

According to the book Design and Analysis of Experiments, pooling has the risk of causing a Type II error, namely combining factors that are actually significant into the error term, which can increase the mean square error value and make it more difficult to detect other significant factors. However, if the degrees of freedom for error are very small (less than six), pooling is recommended because it can improve the accuracy of the analysis [15]. In this study, the degrees of freedom for error obtained were 2, thereby satisfying the condition for applying pooling, as recommended when the degrees of freedom are limited [15]. This process was carried out using Minitab software, in which the factor with the smallest contribution and statistically insignificant effect, namely curing time, was automatically combined into the error component. Thus, although this parameter was not displayed separately in the ANOVA table, its influence was still considered in the model through the error value, resulting in a more stable and representative analysis. Considering the obtained contribution values, the layer thickness and exposure time parameters remained the most influential factors affecting the hardness of the photopolymer resin, and therefore could be used as the basis for determining the optimal parameters in the SLA 3D printing process. Nevertheless, the Taguchi method can still be used to determine the optimal parameter combination based on the S/N ratio values and the contribution of factors to the research response.

Based on the results of the analysis, the layer thickness parameter is the most dominant factor influencing the hardness value of the photopolymer resin. This is because layer thickness has a direct effect on the quality of interlayer bonding. Although several previous studies have reported that smaller layer thickness can improve interlayer bonding and the mechanical properties of materials [5], [8], this study shows that a layer thickness of 0.20 mm produced the highest hardness value. This indicates that a thinner layer does not always guarantee higher hardness, especially when combined with specific exposure energy and resin characteristics. This difference is likely due to the characteristics of the ABS-Like Resin Pro 2 material used, as well as the interaction between layer thickness and exposure time under the applied processing conditions, and possible non-linear interaction between process parameters in SLA printing. These results indicate that the effect of layer thickness on hardness is not determined solely by the layer size, but also by the material characteristics and the combination of other process parameters.

The exposure time parameter also affects hardness because it determines the duration of UV exposure during the photopolymerization process, which directly influences the degree of polymer network formation. The longer the exposure time, the higher the degree of cross-linking formed, thereby increasing material hardness. However, excessive exposure time can lead to overcuring, which may result in non-uniform microstructure and internal stress accumulation. This is consistent with the study by [16].

The washing time parameter influences the cleaning process of uncured resin residues using isopropyl alcohol (IPA), which can also interact with the partially cured polymer surface. Optimal washing improves surface quality, while excessive washing time may cause material softening due to solvent penetration, as IPA may diffuse into the partially polymerized network and reduce surface rigidity. This is supported by the study by [7], which states that washing time has a significant effect on material hardness , although in this study the effect was not statistically significant, it still contributed to the overall variation in hardness.

Meanwhile, the post-curing time (curing time) parameter shows a smaller effect compared to the other parameters. This indicates that most of the photopolymerization already occurs during the printing and exposure stages. Therefore, variations in post-curing time within the tested parameter range do not significantly affect material hardness. However, post-curing still contributes to improving the mechanical properties of the photopolymer resin [8], primarily by completing residual polymerization and stabilizing the polymer network.

6. Confirmation Experiment

The confirmation experiment was conducted to verify the parameter optimization results obtained from the Taguchi method analysis. The purpose of this experiment was to ensure that the determined optimal parameter combination was truly capable of producing a better hardness value compared to the initial conditions. The confirmation test results were compared with the predicted values obtained from the Taguchi method. The obtained values were not required to be exactly the same; however, they were expected to be close to the predicted values. If the difference between the confirmation results and the predicted values was relatively small, then the resulting prediction model could be considered valid and capable of representing the optimal process conditions. In this study, the specimens were printed using the optimal parameter combination obtained from the prediction results, followed by hardness testing using a Shore D type durometer with five measurement points on each specimen according to the previous testing method. The confirmation experiment testing results are presented in Table 10.

Table 10. Confirmation Experiment Results

Hardness Testing Values (Shore D)					Average
Points 1	Points 2	Points 3	Points 4	Points 5	
87,5	89	87	88	87,5	87,8

Based on the test results, the average hardness value obtained was 87.8. This value is close to the Taguchi method predicted value of 88.0333, with a relatively small difference. This indicates that the confirmation experiment results were able to validate the Taguchi method prediction results; therefore, the applied method can be considered sufficiently accurate in determining the optimum parameters in the SLA 3D printing process.

CONCLUSION

Based on the results of the research and analysis conducted on the optimization of SLA 3D printing process parameters on the hardness of photopolymer resin using the Taguchi method, layer thickness showed the largest relative contribution to hardness variation at 47.24%, followed by exposure time at 34.62% and washing time at 14.21%. Meanwhile, curing time had the smallest contribution and was pooled into the error term in the ANOVA analysis. These results suggest that the investigated process parameters contributed more to hardness variation than the post-processing parameters evaluated in this study. However, ANOVA results indicated that none of the investigated factors were statistically significant at the 95% confidence level ($p > 0.05$).

Therefore, the contribution percentages should be interpreted as relative influences within the experimental range rather than as statistically significant effects.

Based on the Taguchi method analysis using the Signal-to-Noise (S/N) ratio, the optimum parameter combination to produce the highest hardness value was obtained, namely a layer thickness of 0.20 mm, exposure time of 9 s, washing time of 5 min, and curing time of 20 min. This parameter combination was able to produce a more optimal hardness response compared to other parameter combinations in this study. Although the ANOVA results showed that all parameters had p-values greater than 0.05, indicating that they were not statistically significant at a 95% confidence level, the Taguchi method remained effective in determining the optimal parameter combination based on the S/N ratio values and the contribution of factors to the research response. The use of Minitab software also supported the data analysis process, resulting in a more systematic and representative outcome.

For future research, it is recommended to increase the number of experiments or testing replications in order to improve the level of statistical significance. In addition, further studies may consider using variations of resin materials, other process parameters, or additional mechanical property tests such as tensile strength and impact resistance to obtain a more comprehensive evaluation of the performance of SLA 3D printed products.

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