ISSN 2828-5174
Ring Mechanical Engineering (RING ME)
Vol. 5 | No. 2 | Desember | Hal. 113-125

GREY RELATIONAL ANALYSIS FOR OPTIMIZING POST-PROCESSING PARAMETERS TO ENHANCE SLA 3D PRINTED MATERIAL HARDNESS

Abdul Hamid[1*)], Rochmad Eko Prasetyaning Utomo[2], Ganda Surahman[3]
[1*)]Automotive Engineering Technology, Politeknik Negeri Banyuwangi, Banyuwangi, Indonesia
[2]Ship Manufacturing Engineering, Politeknik Negeri Banyuwangi, Banyuwangi, Indonesia
[3]Building Construction Engineering Technology, Politeknik Negeri Banyuwangi, Banyuwangi, Indonesia
[*)]Corresponding author: abdulhamid@poliwangi.ac.id

ABSTRACT

The demand for durable custom vehicle components requires enhancing the mechanical characteristics of Stereolithography (SLA) materials, which are generally brittle—a gap that must be addressed through post-processing optimization. This study aims to identify the optimal post-processing parameter combinations to maximize the hardness of SLA resin using the Grey Relational Analysis (GRA) method. The experimental design followed a Taguchi L_9 orthogonal array, testing four factors Washing Time, Curing Time, Annealing Time, and Annealing Temperature at three levels each, with Shore D hardness as the quality response. The results demonstrated a significant increase in hardness from a baseline of 79.2 Shore D to 82.5 Shore D under optimal conditions. The GRA identified the combination of 15 min Washing Time, 25 min Curing Time, 30 min Annealing Time, and 80°C Annealing Temperature as the optimum setting, resulting in a 16.4% improvement in the Grey Relational Grade (GRG) compared to the experimental mean. ANOVA results confirmed that Washing Time (50.79% contribution, P=0.028) and Annealing Time (41.49% contribution, P=0.034) were the most significant factors ($P < 0.05$) influencing hardness variation. Conversely, Curing Time was found to be insignificant (P=0.189), suggesting that 15 minutes is sufficient, while residual monomer removal and thermal stress relief during annealing are more critical. Overall, this study concludes that enhancing SLA material hardness depends heavily on thorough cleaning and controlled heat treatment.

Keywords: SLA Hardness, Grey Relational Analysis, Washing Time, Annealing Time

INTRODUCTION

The demand for custom automotive components has experienced a significant increase, driven by consumer desire for personalization and unique modifications. This trend is no longer exclusive to the luxury automotive sector but has expanded into the two-wheeled vehicle segment and interior components. Rapid advances in additive manufacturing technology have opened vast opportunities to realize these complex designs. 3D printing technology has evolved rapidly from mere prototyping to a production method for functional components using various materials [1]. Among the available methods, Stereolithography (SLA) stands out as a preferred choice due to its ability to print intricate details with high precision and smooth surface finishes. In the context of functional automotive components, the use of ABS-like SLA resin holds great practical significance because its characteristics mimic the toughness and impact resistance of conventional ABS plastic, which are highly required for both exterior and interior vehicle components [2].

However, a fundamental challenge in the functional application of SLA products is ensuring adequate mechanical strength. SLA is based on the photopolymerization of liquid resin. Despite their visual superiority, SLA resin materials tend to be more brittle compared to conventional thermoplastic materials. Resin composition and additives play a vital role in determining the viscosity and final properties of the material [3]. Therefore, for applications requiring resistance to mechanical loads or friction such as vehicle components improving material characteristics is absolutely necessary. Current developments in polymer materials must move toward multi-functionality and enhanced durability [4].

SLA resin materials are based on liquid resin photopolymerization, which often leaves residual monomers or incomplete polymer chain bonds after printing. Consequently, the stages of washing, curing, and annealing become the crucial focus of this research. Optimal washing is vital to remove residual liquid resin trapped in surface micro-details, which, if not cleaned, can inhibit the effectiveness of UV light penetration during curing [5]. Furthermore, post-curing is required to maximize the degree of polymerization conversion, while annealing plays a role in reducing residual stress and increasing the polymer crystallinity arrangement to achieve higher dimensional stability and hardness [6].

Although literature on additive manufacturing has extensively explored the optimization of in-situ parameters such as print orientation and layer thickness [7], [8] there is a tendency within the scientific community to treat the post-processing stage as a non-variable, supplementary procedure. Most studies assume that the final mechanical properties are determined within the build chamber, whereas the functional reality of photopolymer resins, especially the ABS-like type, is determined by the molecular structural integrity formed during the post-processing phase.

The final quality of a 3D-printed product is influenced by many variables. While printing process parameters have a significant impact on structural integrity and specimen hardness [7], [8] optimizing printing parameters alone is often insufficient. Post-processing stages serve as the next determinant key. This process generally involves UV light exposure (post-curing) and heat treatment (annealing). There is a positive correlation between post-print UV irradiation duration and the increase in hardness and tensile strength, as this process completes the polymerization of unreacted carbon chains [9], [10]. Besides duration, Bayarsaikhan et al. [11] emphasized that the temperature during post-curing also affects biocompatibility and mechanical properties by reducing residual monomers that can weaken the structure. In addition to curing, the annealing (heating) method offers potential for microstructure improvement. Research on the influence of annealing temperature has found an optimal temperature range capable of reducing residual stress and increasing polymer crystallinity [12]. This aligns with the principle of material strengthening to achieve better dimensional stability. However, the determination of these parameters must be precise; errors in determining time or temperature can lead to material degradation or over-curing.

Given the numerous variables involved—from printing parameters to post-processing—conventional optimization or trial-and-error approaches become inefficient. Some researchers have attempted computational approaches, using Artificial Neural Networks (ANN) and the Taguchi method to optimize tribology characteristics [13], [14]. While these methods are effective, this research requires an approach capable of handling multi-response characteristics with complex data uncertainty to balance various post-processing parameters. Considering the interdependence between post-process parameters, a trial-and-error approach is highly inefficient. In this study, the Grey Relational Analysis (GRA) method was chosen as the optimization solution. GRA was selected due to its reliability in handling systems with high levels of uncertainty and limited data ("grey" systems). Unlike conventional statistical methods, GRA can integrate various performance responses into a single value (Grey Relational Grade), making it highly effective for optimizing complex manufacturing process parameters with strong variable interactions [15], [16].

Therefore, this research focuses on the "Optimization of SLA 3D Printing Post-Processing Parameters on Material Hardness Characteristics Using the Grey Relational Analysis (GRA) Method." The parameters to be optimized include washing time, curing duration, annealing temperature, and annealing duration. The optimization results will be validated using a standard hardness test, namely ASTM D2240 [17]. By obtaining the optimal combination of post-processing parameters, it is expected that SLA-printed materials can achieve adequate hardness standards for application as tough, high-quality custom vehicle body components.

METHOD

1. Research Methodology Workflow

his study was systematically conducted following structured stages to ensure data validity and optimization accuracy. The research workflow commenced with a literature review, followed by material and equipment preparation, and experimental design using the Taguchi method. Subsequently, the process involved printing and post-processing phases, hardness testing, confirmation experiment, and concluded with data analysis using Grey Relational Analysis (GRA).

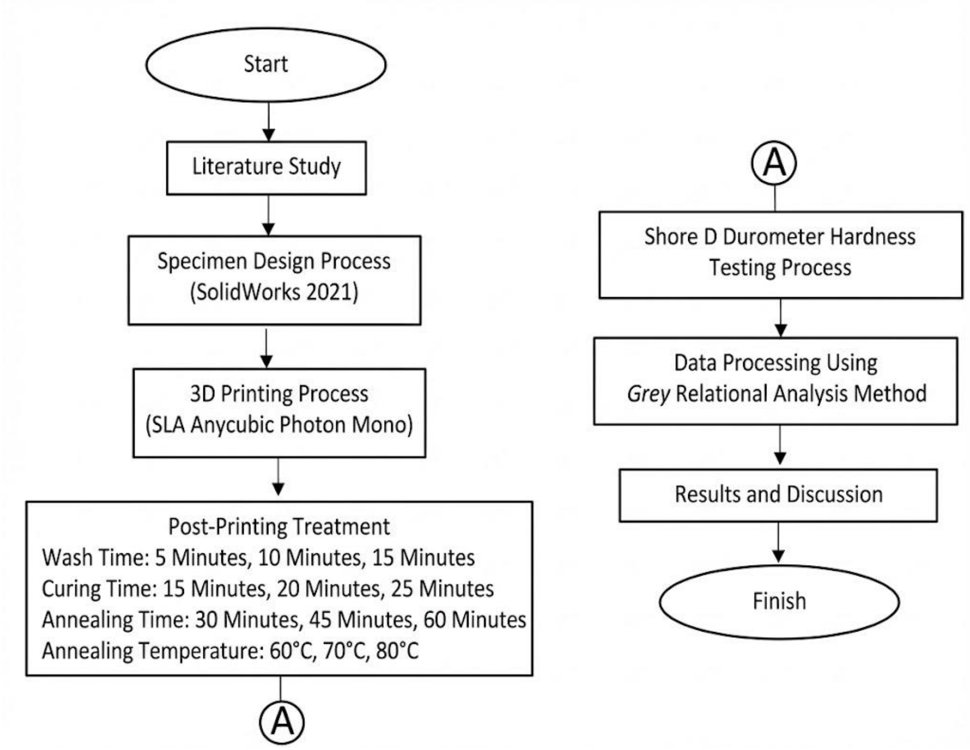

Figure 1. Research methodology workflow

2. Design Of Experiments

This study employs a robust Taguchi L9 orthogonal array (3^4) for the design of experiments. Following the design, a simultaneous optimization stage is carried out using the Taguchi-Grey method. The selection of process parameters and their respective levels are presented in Table 1 and the experimental matrix

Table 1. Research parameters and their levels

Faktor	Level 1	Level 2	Level 3
Time wash	5 minutes	10 minutes	15 minutes
Time curing	15 minutes	20 minutes	25 minutes
Time annealing	30 minutes	45 minutes	60 minutes
Temperature annealing	60°C	70°C	80°C

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

Experiment	*Time wash* (min)	*Time curing* (min)	*Time annealing* (min)	*Temperature annealing* (°C)
1	5	15	30	60
2	5	20	45	70
3	5	25	60	80
4	10	15	45	80
5	10	20	60	60
6	10	25	30	70
7	15	15	60	70
8	15	20	30	80
9	15	25	45	60

Tables 1 and 2 delineate the interconnected experimental layout, which constitutes the independent variables of the research. As an illustration, the first experimental run in Table 2 involves a washing time of 5 min, a curing time of 15 min, an annealing time of 30 min, and an annealing temperature of 60°C. Each trial was executed as a single run, with the resulting specimens subsequently assessed for dimensional fidelity and morphological characteristics to ensure optimal results.

3. Experimental Materials

For the fabrication of the hardness test specimens, Anycubic ABS-Like Resin Pro 2 was utilized, procured from Anycubic (Shenzhen Anycubic Technology Co., Ltd., China). Additionally, 96% alcohol was employed during the washing stage to eliminate any uncured resin residues adhering to the specimen surfaces. The comprehensive characteristics of this resin are detailed in Table 3.

Table 3. Material properties of Anycubic ABS-Like Pro 2 resin

Feature	Value
Solidify wavelength	405 nm
Shelf life	1.5 years
Hardness (D)	82-84D
Viscosity @25°C	300-400 mpa.s
Liquid density	1.05 g/cm^3
Solid density	1.25 g/cm^3
Tensile strength	35-45 MPa
Elongation	35-40 %
Bottom exposure	20-60 s
Normal exposure	5-15 s

4. Research Equipment

The specimens were fabricated using the SLA (Stereolithography) technique on an Anycubic Photon Mono 3D printer. Post-printing processes, specifically washing and curing to remove and solidify resin residues, were performed using an integrated Anycubic Wash and Cure 2.0 system to maintain specimen integrity. The CAD models were initially developed in SolidWorks and exported as STL files. These files were subsequently imported into the Photon

Workshop slicer to define the layer thickness and printing parameters. Figure 3 illustrates that a 0° build orientation was utilized for all specimens.

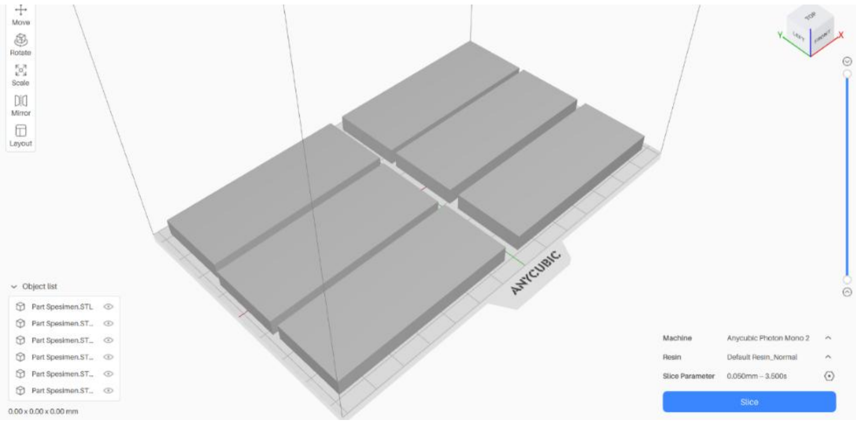

Figure 2. Orientation of the specimen on the build plate 0°

Detailed printing parameters and the Design of Experiment (DoE) utilized for specimen fabrication are tabulated in Tables 1 and 2. The SLA fabrication process was executed using the pwmx sliced files produced by the slicing software, incorporating pre-defined printing parameters. Following the build, specimens were cleaned using a 96% alcohol wash for the designated time. Post-processing continued with curing and annealing treatments, where the variations in curing time, annealing temperature, and annealing duration are documented in Table 2. For each experimental condition, nine specimens were prepared. These rectangular specimens, measuring 65 × 25 × 6 mm, were fabricated in adherence to the ASTM D2240 standard [5], as shown in Figure 2.

5. Printing Parameters

Resin printing parameters were maintained as fixed or controlled variables due to their substantial impact on the quality of the 3D-printed specimens. For each experimental run, nine specimens were evaluated. Following the provided figure, the descriptions of the respective printing parameters are as follows:

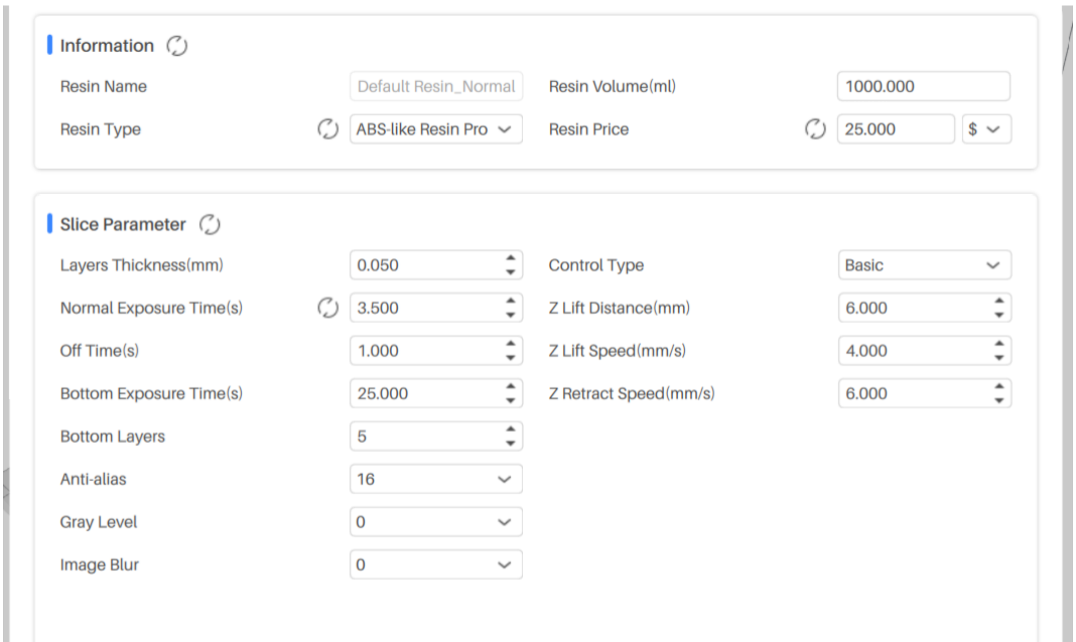

Figure 3. Configuration of controlled printing parameters within the Anycubic Photon Workshop interface

1. Resin Information
   - Resin Name: Default Resin_Normal The name of the resin profile utilized as a reference for the configuration settings.
   - Resin Type: ABS-like Resin Pro The classification of the resin used, which possesses characteristics mimicking ABS plastic; it is suitable for prints requiring high strength and durability.
   - Resin Volume (ml): 1000.000 The total volume of resin available in milliliters (ml).
   - Resin Price: 0.000 The resin cost has not been inputted; this field is typically used for print cost estimation.
2. Slice Parameters as Controlled Variables
   - Layer Thickness (mm): 0.050 The thickness of each printed layer; thinner layers result in higher resolution and finer detail fidelity.
   - Normal Exposure Time (s): 3.500 The UV exposure duration for standard layers, which influences the structural strength and detail sharpness.
   - Off Time (s): 0.500 The delay interval between exposures, allowing the resin to settle and preventing overheating of the light source.
   - Bottom Exposure Time (s): 25.000 The exposure duration for the initial base layers, typically set longer to ensure strong adhesion to the build platform.
   - Bottom Layers: 5 The specific number of initial layers printed using the bottom exposure time for foundation stability.
   - Anti-alias: 16 A setting used to smooth the edges of the object; higher values result in a smoother surface finish.
   - Gray Level: 0 Controls the grayscale levels of the sliced images, usually utilized for contrast adjustment during printing.
   - Image Blur: 0 The setting for applying a blur effect to the sliced images; a value of 0 indicates no blur is applied.
   - Control Type: Basic The printing control mode; "Basic" indicates standard settings without advanced feature modifications.
   - Z Lift Distance (mm): 6.000 The vertical distance the platform rises after each layer is successfully printed.
   - Z Lift Speed (mm/s): 4.000 The upward velocity of the platform, which influences the total build time.
   - Z Retract Speed (mm/s): 6.000 The velocity at which the platform descends back to the printing position; this is critical for the stability of the subsequent layer.

6. Testing Procedure

Hardness measurements were carried out using a Digital Shore D Durometer, which was integrated into a drill press spindle to ensure uniform pressure application. The testing was performed under ambient laboratory conditions. For each specimen, data were recorded at five distinct locations with a minimum spacing of 6 mm between indentations. The starting point was located at least 12 mm from the specimen edge, as detailed in the layout in Figure 4. During the procedure, specimens were positioned perpendicularly to the indenter. The drill press lever was engaged to drive the indenter into the material surface after ensuring full contact of the pressure foot, guaranteeing the precision of the hardness values.

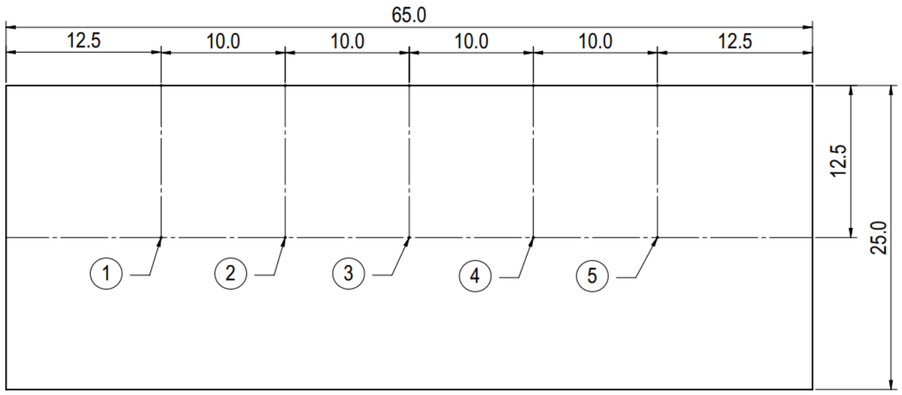

Figure 4. Schematic of measurement points on the ASTM D2240 test specimen

7. Data Analysis Procedure

Data analysis was performed to optimize the process parameters using an integrated approach of the Taguchi method and Grey Relational Analysis (GRA). Although GRA is widely recognized as a multi-response optimization method, its application in this study for a single response (hardness) is justified by its superior capability in handling systems with limited information and high levels of uncertainty (grey systems). Given the complexity of non-linear interactions among SLA post-processing parameters, GRA provides a more robust evaluation mechanism by calculating the degree of relation relative to an ideal reference sequence—a comprehensive analysis that conventional statistical optimization methods often fail to achieve. The analytical stages are as follows:

1. Experimental Design and S/N Ratio Calculation:
   The experimental design matrix was developed using Minitab 18 and Microsoft Excel. The experimental results were converted into Signal-to-Noise (S/N) ratios. For hardness characteristics, the Larger-the-Better quality characteristic was applied, as a higher hardness value is desired. The S/N ratio for the larger-the-better characteristic is calculated using the following formula:

$$\eta = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right)$$

2. Data Normalization (Data Pre-processing):
   The S/N ratio values were normalized to a range between 0 and 1 to fulfill the requirements of GRA. This step eliminates the scaling effects of different units and prepares the data for the relational coefficient calculation.
3. Grey Relational Coefficient (GRC) Calculation:
   The relational coefficient for the response was calculated based on the deviation sequence and a distinguishing coefficient (ζ) In this study, a distinguishing coefficient of ζ = 0.5 was utilized to balance the stability of the analysis.
4. Grey Relational Grade (GRG) Calculation:
   The GRG was determined by averaging the GRC values to rank each experimental run. The highest GRG value indicates the most optimal combination of post-processing parameters.
5. Analysis of Variance (ANOVA):
   ANOVA was performed to determine the percentage contribution of each factor (Washing Time, Curing Time, Annealing Time, and Annealing Temperature) to the variation in hardness characteristics. This identifies which parameters significantly influence the final material properties.

6. Validation and Conclusion:
   The predicted optimal conditions were compared with the results of a confirmation (actual) experiment to validate the model's accuracy and draw final research conclusions.

RESULTS AND DISCUSSION

The results for the hardness testing of Stereolithography (SLA) specimens, along with the post-processing parameter optimization via the Taguchi-Grey Relational Analysis (TGRA) approach, are discussed below.

1. Hardness Measurement Results

In adherence to ASTM D2240 [5], Shore D hardness tests were performed on the nine L9 experimental runs. Each specimen was subjected to five indentations (Points 1–5) to guarantee the reliability and consistency of the data. Figure 5 depicts the direct measurement data, and the calculated mean hardness values are summarized in the chart shown in Figure 6

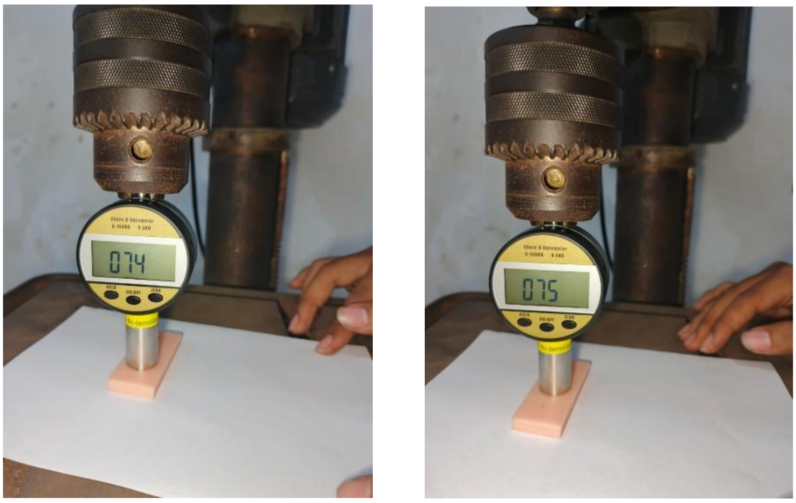

Figure 5. Measurement of material hardness with a Digital Shore D Durometer

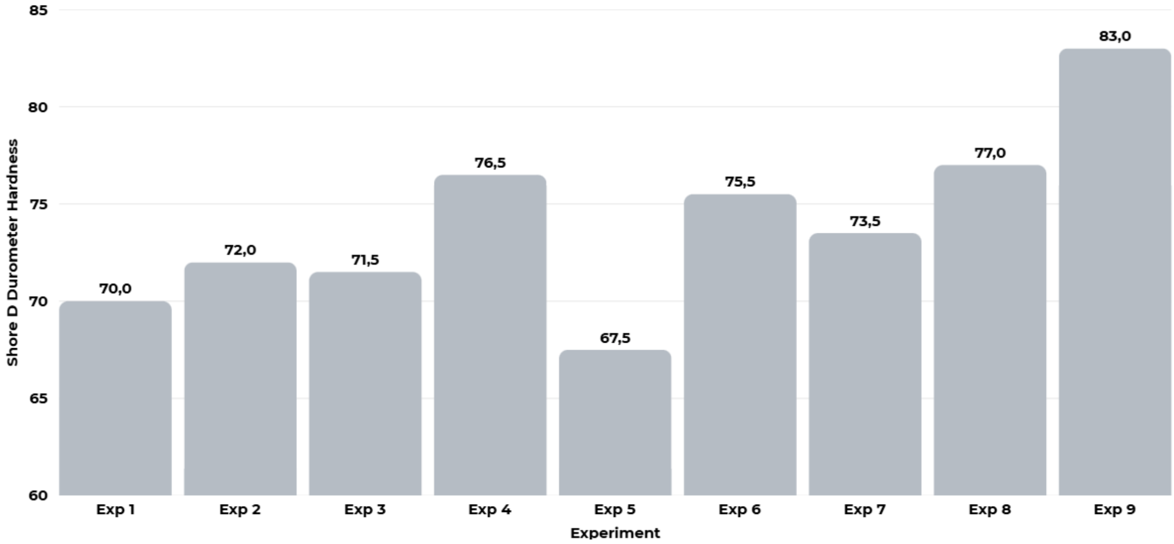

Figure 6. Mean hardness test results using a Digital Shore D Durometer

2. Results of Taguchi-Grey Relational Analysis (TGRA) Data Processing

Data analysis was conducted to transform the response (or in this case, a single optimized response) into a single evaluative index. This process integrates the robustness of the Taguchi Method with the optimization capabilities of Grey Relational Analysis (GRA).

The data analysis workflow commenced with the calculation of the Signal-to-Noise (S/N) Ratio. This step converts raw experimental data into S/N Ratio values. Since the investigated characteristic is hardness, where a higher value is desirable, the "Larger-the-Better" criterion was applied. Following the determination of the S/N Ratio for each experiment, the process continued with Data Normalization (Data Pre-processing). This stage scales the S/N Ratio values into a uniform range between 0 and 1, which is a prerequisite for GRA. Subsequently, the Deviation Sequence was calculated by determining the absolute difference between the reference sequence (the ideal value, which is 1) and the normalized value of each experiment.

From these deviation values, the Grey Relational Coefficient (GRC) was computed to measure the degree of correlation between the experimental data and the ideal reference, using a distinguishing coefficient typically set at $\zeta = 0.5$. The final stage involved calculating the Grey Relational Grade (GRG), derived from the average of the GRC values. The GRG values were then used to rank each experimental run, where the highest GRG indicates the most optimal parameter combination. The complete results of the Taguchi-Grey analysis are summarized in Table 4 below.

Table 4. Results of Taguchi-Grey Relational Analysis for Each Experimental Run

Taghuci Method				Grey Relational Analisys			
Exp	MEAN	SNRA	CV1	*(Data Normalization)*	*Nilai Deviation Squance*	*Grey Relational Coefficient (GRC)*	*Grey Relational Grade (GRG)*
1	72,7	37,20672388	0,048777505	0,466	0,534	0,484	6
2	71,8	37,11797202	0,020657935	0,414	0,586	0,460	7
3	66,4	36,41576756	0,052006918	0,000	1,000	0,333	9
4	77,2	37,74936559	0,016889125	0,786	0,214	0,700	4
5	67,5	36,58550353	0,007407407	0,100	0,900	0,357	8
6	78,7	37,91367976	0,023169736	0,883	0,117	0,810	3
7	74,3	37,41892761	0,009028538	0,591	0,409	0,550	5
8	80,4	38,09562416	0,029954215	0,990	0,010	0,980	2
9	80,5	38,11279275	0,01756787	1,000	0,000	1,000	1

The calculated GRG values were utilized to establish the ranking of the experimental trials. The highest GRG corresponds to the most effective parameter combination. As shown in Table 4, Experiment 9 secured the first rank (GRG = 1.000), representing the optimal post-processing setting. In contrast, Experiment 3 was ranked ninth (GRG = 0.333), indicating the lowest-performing combination. Subsequently, the mean GRG response was determined to identify the optimal level for each factor, with the results summarized in Table 5.

Table 5. Response Table for Grey Relational Grade (GRG)

	1	2	3	Delta	Rank
Time wash (Min)	0,426	0,622	**0,843**	0.417	1
Time curing (Min)	0,578	0,599	**0.714**	0.136	3
Time annealing (Min)	**0,758**	0.720	0.413	0.345	2
Temperature Annealing (Celcius)	0,614	0.607	**0.671**	0.064	4

The optimal parameter combination was predicted based on the mean GRG calculation for each factor level. The combination yielding the highest mean GRG values represents the optimum configuration, which is detailed in Table 6.

Table 6. Optimum Parameter Combination

Optimum Combination		
Parameter	Level	Nilai
Time wash (Min)	3	15 min
Time curing (Min)	3	25 min
Time annealing (Min)	1	30 min
Temperature Annealing (Celcius)	3	80°C

The predicted optimal parameter settings were derived from the mean GRG values for each factor using Minitab 2022 analysis software, the results of which are summarized in Table 7.

Table 7. Predicted Optimal Parameters for S/N Ratio and Shore D Hardness

Time wash	Time curing	Time Annealing	Temperature Annealing
15	25	30	80^0
		S/N Ratio	Mean
		38,3268	82,3667

he confirmation experiment, utilizing the optimal settings of 15 min washing time, 25 min curing time, 30 min annealing time, and an 80°C annealing temperature, yielded a hardness value of 82.5 Shore D. The discrepancy between the actual experimental result and the predicted value was found to be 0.133.

3. Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) was applied to identify which process parameters significantly influence the quality characteristics of the response. In the context of optimization using Grey Relational Analysis (GRA), ANOVA was utilized to analyze the Grey Relational Grade (GRG) values to determine which factors provide the most substantial contributions.

The ANOVA results are presented in a table containing key statistics: Degrees of Freedom (DF), Sum of Squares (SS), Mean Squares (MS), F-values, and the percentage contribution (C) associated with each factor. The following hypotheses were employed:

- **Null Hypothesis** (H_0)**:** The factor does not significantly affect the response.
- **Alternative Hypothesis** (H_1)**:** The factor significantly affects the response.

Factor significance was determined based on two primary criteria:

1. **P-value:** A factor is considered significant if the calculated P-value is less than 0.05 (P-value < 0.05), leading to the rejection of H_0 and acceptance of H_1
2. **F-value:** A large F-value indicates a significant influence. Formally, if the calculated F-value exceeds the F-value from the statistical table, the factor is deemed statistically significant.

Consistent results between the F-test P-value < 0.05) confirm that the process parameter contributes meaningfully to the optimized performance characteristics. Based on the ANOVA results for GRG values (Table 8) at a 0.05 significance level, it was found that Washing Time and Annealing Time are statistically significant factors, with P-values of 0.028 and 0.034, respectively.

Table 8. Analysis of Variance (ANOVA) for Grey Relational Grade (GRG)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Time wash	2	0,261988	50,79%	0,261988	0,130994	34,86	0,028
Time curing	2	0,032351	6,27%	0,032351	0,016175	4,30	0,189
Time annealing	2	0,214021	41,49%	0,214021	0,107010	28,47	0,034
Error	2	0,007516	1,46%	0,007516	0,003758		
Total	8	0,515876	100,00%				

The ANOVA results identify Washing Time as the most dominant factor, contributing 50.79% to the variation, followed by Annealing Time at 41.49%. This dominance suggests that the thoroughness of removing unpolymerized resin and the subsequent relief of residual stresses are the primary drivers of hardness in SLA-printed ABS-Like resin. It is important to note that the exclusion of Annealing Temperature from the ANOVA table was a strategic decision to resolve the "saturated model" error. In an L9 3^4 orthogonal array, including all four factors at three levels each consumes all 8 available degrees of freedom. By pooling the least significant factor Annealing Temperature into the error term, the model gained the statistical power required to validate the significance of the other three parameters. This approach is standard practice in Taguchi-based experimental designs to ensure the mathematical validity of the F-test and P-value < 0.05 results.

Washing time ensures the removal of unpolymerized monomers, which otherwise act as impurities that create weak points or discontinuities. These residues hinder the cross-linking process and directly reduce the final hardness [9]. However, the interaction between solvent and polymer must be carefully controlled. Experiment 3 exhibited an anomaly with the lowest mean hardness compared to other combinations. This phenomenon can be explained by contradictory interactions between post-processing parameters. In this instance, the low hardness was likely caused by excessive washing time paired with a very short curing duration. Prolonged washing in solvents like Isopropyl Alcohol (IPA) can cause the solvent to diffuse into the outer layers of the specimen, leading to softening and swelling of the immature polymer structure. If followed by an insufficient UV curing cycle, trapped solvent residues inhibit the completion of molecular cross-linking. Research indicates that such chemical residues in the early stages of post-processing can permanently degrade the structural integrity of the polymer [15].

The Curing Time factor provided the lowest contribution at 6.27% and was found to be statistically insignificant (P-value 0.189). This lack of statistical significance does not imply that the curing process itself is unimportant [3], [10]. Indeed, adequate curing is fundamental for achieving maximum cross-linking. Experimental results show that increasing curing time correlates positively with material hardness up to a certain optimal point.

SLA ABS-Like resin relies on photopolymerization; post-print UV exposure triggers remaining photo-initiators to complete the polymer chains trapped within the resin matrix. Longer UV photon penetration increases cross-linking density, which manifests macroscopically as increased surface hardness. This aligns with Steyrer et al. [18], who stated that the degree of polymerization conversion determines the final strength of thermoset structures. However, the results indicate that the time variation tested (15 to 25 minutes) did not produce sufficient variability to exceed the significance threshold compared to the more critical washing and annealing stages.

The Annealing Time factor holds a significant contribution of 41.49% (P-value 0.034). This thermal process, when applied for an optimal duration (30–45 minutes), functions to reduce the residual stresses formed during the rapid thermal contraction of the printing and UV curing stages. This allows the polymer to achieve a more stable and dense bonding structure [4], [11].

Furthermore, annealing above the glass transition temperature but below the degradation point facilitates stress relief. During SLA printing, residual stresses accumulate due to thermal shrinkage and localized polymerization contraction. The heat provided during annealing gives polymer chains the kinetic energy to rearrange into a more stable and compact configuration. [19] confirmed that such controlled heat treatment enhances microstructural order, directly improving the material's resistance to indentation and overall hardness. In summary, the impact of washing thoroughness and residual stress control via annealing is far more critical in governing quality variation and robustness than minor increases in curing duration within the experimental range investigated.

CONCLUSION

Based on the optimization of post-processing parameters for Anycubic ABS-Like Pro 2 resin using the Taguchi-Grey Relational Analysis (TGRA) method, it is concluded that the optimal configuration to maximize and stabilize material hardness is achieved at level A3-B3-C1-D3. This specific combination consists of a 15-minute washing time, 25-minute curing time, 30-minute annealing time, and an annealing temperature of 80°C, which collectively yielded the highest Grey Relational Grade (GRG). The ANOVA results further confirm that Washing Time and Annealing Time are the most statistically significant factors ($P < 0.05$), contributing 50.79% and 41.49% respectively to the overall quality variation, while variations in curing time and annealing temperature were found to be statistically insignificant within the tested range.

Validation through a confirmation experiment resulted in a hardness value of 82.5 Shore D, demonstrating high model reliability with a minimal deviation of only 0.133 from the predicted value. Compared to the baseline or lower-performing configurations (such as Experiment 3), this optimal setting represents a significant enhancement in mechanical performance. Ultimately, the study highlights that the thorough removal of residual monomers during the washing stage and the effective relief of internal stresses through annealing are the most critical mechanisms for achieving superior structural integrity and optimal mechanical properties in SLA 3D-printed photopolymer materials.

ACKNOWLEDGEMENTS

The authors would like to thank Politeknik Negeri Banyuwangi for financing this study via the 2024 Internal Research Grant (DIPA). We highly value the collaboration of our research colleagues and the technical support provided by the Mechanical Engineering students during data collection and laboratory trials. The support from the Department of Mechanical Engineering in providing high-quality facilities and infrastructure was crucial to our results. We also extend our thanks to all parties whose invaluable assistance and encouragement helped finalize this research successfully.

REFERENCES

[1] Shahrubudin N, Lee TC, Ramlan R. An overview on 3D printing technology: Technological, materials, and applications. Procedia Manuf. 2019;35:1286-96.
[2] Zguris Z. The Performance of Integrated 3D Printing Materials: ABS-like Resin Properties. Int J Rapid Manuf. 2016;5(3):210-25.
[3] Kruth J, Mercelis P, Van Vaerenbergh J, Froyen L, Rombouts M. Binding mechanisms in selective laser sintering and selective laser melting. Rapid Prototyp J. 2005;11(1):26-36.
[4] Bekas DG, Hou Y, Liu Y, Panesar A. 3D printing to enable multifunctionality in polymer-based composites: A review. Compos Part B Eng. 2019;179:107540.
[5] Sames WJ, List FA, Pannala S, Dehoff RR, Babu SS. The metallurgy and processing science of metal additive manufacturing. Int Mater Rev. 2016;61(5):315-60.
[6] Garcia EA, Ayrilmis N, Fan J, Benson R. Effect of post-processing techniques on mechanical properties of 3D printed polymers. J Polym Environ. 2020;28(12):3021-35.

[7] Wang X, Zhang Y, Li M, Chen W. Effect of printing parameters on mechanical properties of 3D printed parts. J Manuf Process. 2020;56:102-12.
[8] Nugroho A, Arifin J. Pengaruh variasi parameter cetak dan post process terhadap tingkat kekerasan spesimen hasil cetak tiga dimensi berbasis stereolithography (SLA). Prosiding SENATIK: Seminar Nasional Teknologi Informasi dan Kedirgantaraan. 2021;6:107-16.
[9] Park HS, Kim SH, Lee JW. Effect of post-curing UV time on the hardness and tensile strength of SLA resin materials. Addit Manuf. 2021;45:102030.
[10] Kim SH, Lee YK. Effect of Post-Curing Time on the Mechanical Properties and Color of 3D-Printed Crown and Bridge Materials. Polymers (Basel). 2022;14(22):4832.
[11] Bayarsaikhan E, Lim JH, Shin SH, Park KH, Park YB, Lee JH, et al. Effects of Post-Curing Temperature on the Mechanical Properties and Biocompatibility of Three-Dimensional Printed Dental Resin Material. Materials (Basel). 2021;14(5):1162.
[12] Zhao L, Huang J, Chen P. Investigation on the effect of annealing temperature on mechanical properties of 3D printed polymers. Mater Des. 2022;213:110332.
[13] Chaudhary R, Kumar N, Singh PK. Optimizing the hardness of SLA printed objects using the artificial neural network and genetic algorithm. J Ambient Intell Humaniz Comput. 2022;13:1-12.
[14] Rifai M. Optimasi Parameter pada 3D Print Resin untuk Menghasilkan Karakteristik Tribologi yang Terbaik menggunakan Metode Taguchi [Skripsi]. Yogyakarta: Universitas Islam Indonesia; 2021.
[15] Kuo CF, Lan WL, Chen CW. Optimization of 3D printing process parameters for mechanical properties using Grey Relational Analysis. Int J Adv Manuf Technol. 2021;115:3671-85.
[16] Lin CL. The use of the orthogonal array with grey relational analysis to optimize the electrical discharge machining process with multiple performance characteristics. Int J Mach Tools Manuf. 2004;44(2-3):227-40.
[17] ASTM International. ASTM D2240-15, Standard Test Method for Rubber Property—Durometer Hardness. West Conshohocken, PA; 2015.
[18] Steyrer B, Neubauer B, Swoboda P, Koch T. Influence of post-curing on the mechanical properties of photopolymers for additive manufacturing. Polymer Testing. 2017;62:232-9.
[19] Rezvani M, Safavi MS, Khosravani MR. Effect of thermal annealing on the mechanical behavior and microstructural order of 3D-printed SLA parts. Mater Chem Phys. 2022;285:126135.