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Technical Paper

Optimizing Surface Finish and Dimensional Accuracy in 3D Printed Free-Form Objects

Farid Wajdi [a,*], Mohd Sazli Saad [b]

[a] Department of Industrial Engineering, Universitas Serang Raya, Serang, Indonesia
[b] School of Manufacturing Engineering, Universiti Malaysia Perlis, Perlis, Malaysia

* Corresponding Author: faridwajdi@unsera.ac.id

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ABSTRACT

3D printing of free-form objects presents inherent complexity due to their organic and intricate shapes. Designers engage with such objects, considering a range of factors including aesthetics, engineering viability, and ergonomic comfort. This research is focused on achieving the most effective printing parameters for a free-form object utilizing the Digital Light Processing (DLP) technique within a 3D printer. Within this study, a squeezed hexagonal tube-shaped CAD model was employed as an experimental subject, following the principles of the Response Surface Method (RSM). The model represents a free-form model that deviates from traditional geometric norms and emphasizes artistic expression and creativity. The research delved into the optimization of printing parameters, particularly layer thickness and exposure time, to enhance the dimensional accuracy and surface quality of the free-form model. Two levels were established for each factor: layer thickness was set at 0.06 mm (low) and 0.08 mm (high), while exposure time was tested at 6 s (low) and 8 s (high). The assessment of surface quality involved a qualitative evaluation employing a digital microscope to identify potential defects and imperfections in the print outcomes. The investigation culminated in the identification of the optimal printing parameters: a layer thickness of 0.0753 mm and an exposure time of 7.2143 seconds, which were interpolated from the two levels of each parameter. This achievement not only enhances the understanding of 3D printing variables in the context of intricate free-form models but also contributes to the broader field of additive manufacturing parameter optimization.

Keywords: 3D printing, free-form model, response surface method, printing parameters optimization, additive manufacturing

INTRODUCTION

The utilization of complex shapes defined by free-form designs is intrinsically influenced by considerations encompassing aesthetics, engineering principles, and ergonomic comfort. From an aesthetic standpoint, the adoption of free-form shapes is inherently subjective and plays a crucial role in shaping the preferences of contemporary consumers [1]. Investing in design shape has an impact on market share. This is evidenced by vehicles with superior design shape having better market performance compared to vehicles with functional and ergonomic advantages [2]. Prominent examples such as supercars emphasize the incorporation of free-form shapes to enhance both aerodynamic efficiency and product image. Furthermore, the engineering landscape employs free-form shapes to shape the aerodynamic contours of aircraft bodies and wings. Meanwhile, within the product comfort domain, free-form designs find applications in diverse areas ranging from car seats to medical devices, handles, computer mice, and more. To address the surging demand for free-form designs in consumer and professional contexts, dedicated methodologies and tools have been developed [3].

The domain of three-dimensional printing (3DP) has experienced an impressive and rapid evolution, penetrating diverse sectors within the manufacturing and engineering domains, and even branching into personal applications [4]. This transformative technology has brought about a democratization of rapid prototyping processes, ushering in enhanced accessibility and cost-effectiveness. Consequently, this evolution has led to a compression of timelines associated with the development of new products, thereby propelling innovation and expediting the journey from conception to realization. The capabilities of 3D printing have been integrated with cutting-edge imaging modalities like CT scans, MRIs, radiographs, and echocardiography to obtain precise results [5]. This synergy has led to a revolutionary transformation in both practical medical procedures and educational paradigms. For practical applications, 3D printing has empowered medical professionals to create patient-specific models that faithfully replicate anatomical structures. These models, derived from real patient data, provide an unprecedented opportunity for surgeons to plan and rehearse complex procedures prior to entering the operating theater. The ability to physically manipulate and interact with an accurate 3D representation of a patient's anatomy contributes to heightened surgical precision, reduced operative risks, and enhanced patient outcomes [6].

Two prominent techniques in the 3DP technology have emerged: Fused Deposition Modeling (FDM) and Digital Light Processing (DLP). Both methodologies operate through incremental layering processes to fabricate tangible objects. FDM involves the utilization of filament materials, commonly composed of thermoplastic polymers, and has recently expanded to encompass metals—a novel iteration building upon the traditional FDM framework [7]. Within FDM, filaments are heated to their respective melting points and extruded through a nozzle, thereby shaping the object layer by layer. Conversely, DLP operates on the principle of VAT photopolymerization, where a liquid material undergoes chemical transformation upon exposure to light, transitioning from a liquid state to a solid one [8], [9]. This technique is heralded for delivering superior surface finishes, heightened dimensional accuracy, and accelerated printing speeds compared to alternative 3D printing methodologies [10]–[12]. In addition, DLP requires less complex or easily removable support structures compared to FDM. Since DLP cures the entire layer simultaneously, supports can be optimized to be minimal and easy to remove [13]. The output of the 3D printing process is markedly contingent on the selection of process parameters, wielding substantial influence on the printed artifacts. Leveraging the DLP technique, 3D printing has evolved to not only facilitate design activities but also to yield high-fidelity physical products. However, the 3DP machines currently lacks standardized configurations for process parameters. The variations in parameter settings can significantly impact printing outcomes, thus emphasizing the critical role of careful parameter selection [14].

Printing complex objects poses a distinct challenge due to prevailing 3D printers operating on a 3-axis framework. Crafting items bearing free-form attributes proves complex, primarily due to their organic configurations [15], [16]. To overcome these challenges, mathematical constructs like Bezier curves, B-Spline curves, and Non-Uniform Rational Basis Spline (NURBS) patches have emerged as powerful tools for representing and translating free-form shapes into the digital domain [17]. However, the transition from mathematical representation to physical manifestation is not without its intricacies. The process of navigating shape deformations that may occur within each segment of an object introduces a layer of complexity. To successfully steer these deformations and achieve accurate and faithful printed representations, the establishment of constraints becomes an essential undertaking [18]. This complex relationship of process parameter optimization, involved geometry translation, and shape deformation management exemplifies the multidisciplinary nature of the challenges encountered in 3D printing. The evolving landscape of additive manufacturing continues to strive toward addressing these complexities, propelling the field toward enhanced accuracy, fidelity, and efficiency. The challenges faced by professionals in 3D printing free-form designs due to a lack of clear parameter guidelines are significant. Consequently, conducting research to acquire the most favorable print parameters for such designs becomes necessary.

Numerous studies have been dedicated to enhancing 3D DLP printed objects, encompassing optimization of printer machinery, materials, and print coordinates. Zhou et al. [19] conducted a study to elevate the precision of 3D printing (3DP) processes and concurrently alleviate dimensional variations in the resulting printed objects. This study embarked on a comprehensive exploration of five influential variables that collectively impact the intricacies of the 3DP outcomes. These variables encompassed layer thickness, over-cure, hatch space, blade gap, and object placement. In their endeavor to comprehend the nuanced interactions of these variables and their consequential effects on 3DP outputs, Zhou and colleagues employed the Taguchi Method—an effective statistical approach renowned for its ability to systematically dissect complex multifactorial relationships. This method facilitated the analysis of the collective impact of the identified variables on the overall quality and accuracy of the printed products.

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The results revealed that optimal conditions for realizing enhanced precision and minimized dimensional deviations in 3DP were contingent on two key factors. Firstly, it was ascertained that employing the shortest possible laser scan duration significantly contributed to elevating the precision of the process. Secondly, the study highlighted the crucial role of an appropriately chosen layer thickness, which emerged as a critical parameter in curbing dimensional inconsistencies and achieving the desired accuracy in 3D printed outcomes. By discerning the complex relationships between these influential variables and their cumulative impact on 3DP results, the study by Zhou et al. underlines the significance of a methodical and data-driven approach in the quest to enhance the quality and precision of 3D printed objects.

Rahmati and Ghadami [20] explored the optimization of key parameters in the 3D printing process. These parameters included layer thickness, over-cure, hatch gap, and hatch fill depth. Each of these factors plays a critical role in shaping the final outcome of a 3D printed object. Layer thickness refers to the vertical dimension of each individual layer that is deposited during the printing process. This parameter significantly impacts the structural integrity and overall precision of the printed object. By varying the layer thickness, the researchers aimed to determine the optimal value that would lead to enhanced print quality and accuracy. Over-cure, another parameter scrutinized by this study, pertains to the degree of curing that takes place during the printing process. If a material is over-cured, it might become excessively rigid or brittle, potentially affecting the mechanical properties of the printed object. Therefore, fine-tuning the over-cure parameter is vital to achieving the desired balance between material strength and flexibility. Hatch gap and hatch fill depth refer to the spacing and the depth of the paths that the 3D printing nozzle follows while depositing material to create each layer. These parameters influence how closely the material is deposited, which in turn affects the surface finish and overall accuracy of the object. Determining the optimal values for hatch gap and hatch fill depth is crucial for achieving smooth, uniform layers and minimizing imperfections. By systematically examining and optimizing these parameters, Rahmati and Ghadami aimed to achieve the highest possible quality and accuracy in their 3D printed objects. In their experimentation, which mirrored Zhou's work [19] with general shapes, layer thickness emerged as the most influential factor impacting 3D printing quality.

Ibrahim et al. [21] conducted a comprehensive investigation to elucidate the intricate interplay between layer thickness and exposure time within the context of 3D DLP printing. Specifically, they explored how these factors influenced the creation of tensile test specimens, with the goal of revealing their implications for both the mechanical characteristics and dimensional features of the printed items. Layer thickness was closely examined to discern its influence on the mechanical performance and accuracy of the fabricated specimens. This dimension dictates the vertical extent of each layer and significantly affects the structural integrity of the printed object. Simultaneously, exposure time, determining the duration of each layer's exposure to light, was meticulously explored due to its role in initiating material cross-linking and solidification. Remarkably, the findings revealed a marginal 3.8% variation in the dimensional accuracy of the 3D DLP printed specimens. This slender discrepancy underscores the precision attainable through the optimization of layer thickness and exposure time. The identification of optimal values for these parameters emerged as a pivotal outcome of the study. These values engendered superior mechanical properties in the printed objects, culminating in heightened mechanical strength and minimized errors in dimensions.

In the study conducted by Bertana et al. [22] focused on a 3D-printed micrometric spring's build accuracy and the behavior of commercial acrylic resin used. Firstly, the build accuracy of the 3D-printed micrometric spring was investigated which refers to how closely the actual physical object matches the intended design in terms of its dimensions and shape. To do this, they used measurements and comparisons to assess the accuracy of the printed spring's dimensions. Secondly, they were particularly investigated in how the chosen material, which was a commercial acrylic resin, behaved during the 3D printing process and afterwards. They found that the accuracy of the printed spring varied depending on the direction in which they were measuring it. Specifically, when looking at the dimensions along the x-y plane, the printed spring was more accurate compared to the intended dimensions. However, when considering measurements in the z-direction, the accuracy was somewhat lower. This discrepancy in accuracy between different directions can be quite common in 3D printing due to the way the layers are built up. Additionally, the transparency of the acrylic resin played a role in the dimensional accuracy of the printed spring.

This means that the level of transparency or translucency of the material affected how precisely the dimensions of the final printed object matched the intended specifications. This study highlighted that the accuracy of 3D-printed objects can be influenced by various factors, including the type of material used, the direction of measurement, and even properties like transparency.

Mathew et al. [23] has conducted an insightful exploration to comprehend and enhance the print quality of microneedles (MNs). This study investigated the influence of the print angle on the resultant needle geometries. By systematically altering the angles at which the microneedles were printed, Mathew and colleagues sought to ascertain the effects of this variable on the accuracy of the printed needle shapes. Beyond geometry, this study extended their investigation into the mechanical properties of the printed MN arrays. Employing a texture analyzer, they conducted mechanical tests to comprehensively evaluate the structural robustness and resilience of the fabricated microneedles. The study exhibited the effect of curing times on the mechanical strength of the microneedles. Specifically, the duration of curing processes was found to significantly influence the strength of the MN arrays. Of particular significance, the study discovered that the angle at which the MNs were printed had a pronounced impact on achieving geometries that closely matched the CAD designs. Moreover, the investigation showed that curing times played a determinant role. The MN arrays, when subjected to a considerable force of 300 N, did not break but rather exhibited flexibility by bending—an observation indicative of their mechanical robustness. Mathew et al.'s study offers a comprehensive exploration of MN print quality optimization, encompassing both geometrical fidelity and mechanical strength. The findings contribute valuable insights for refining the precision of microneedle fabrication, offering implications that extend to a range of applications including transdermal drug delivery and medical diagnostics. This research highlights the complex relationship between printing parameters, geometries, and material properties in the microscale additive manufacturing.

The analysis of existing studies highlights the critical role of layer thickness in shaping the accuracy of 3D printing outcomes. Layer thickness is defined by the vertical extent of successive resin additions, each subject to cumulative UV light exposure within specified intervals [24]. This parameter significantly influences the printing duration required. The exposure time constitutes the second crucial process parameter, dictating the duration for which each layer is subjected to light irradiation. This temporal factor dictates the quantum of photons a material receives, initiating and propagating reactions during the cross-linking process. The exposure time's role is especially critical for achieving strong adhesion between layers [21].

This research aims to determine the best process parameters for a commercial 3D DLP printer, specifically layer thickness and exposure time, to improve the dimensional accuracy and surface finish of 3D printed free-form models. The study seeks to establish the ideal printing process parameters capable of yielding optimal results in terms of accuracy and finish for intricate free-form models. This research will focus on the DLP technique within 3D printing and will not explore other methods like FDM in depth.

METHODS

Materials

The experiment employs Anycubic Resin Clear UV 405 nm (552 mpa.s) and Anycubic Zero 3D printer machine (Shenzen Anycubic Technology, China). The printer is working with Digital Light Processing (DLP) technique and featured with 480 Pixels resolution and 0.01 mm accuracy at Z-axis. The maximum build volume is 97 mm (L), 54 mm (W), and 150 mm (H). The resin and 3D printer were selected due to its availability and affordability. Isopropyl alcohol (IPA 96%) is used to rinse the printed results.

Printing Fabrication

The free-form model was created using 3D CAD software Rhinoceros 7 (Robert McNeel & Associates, USA). The model has outer dimensions of 18 x 10 mm, and 2 mm of wall thickness. The model is exhibited in Figure 1. The original CAD file (*.3dm) was converted into a stereolithographic model (*.stl). The *.stl format is commonly used

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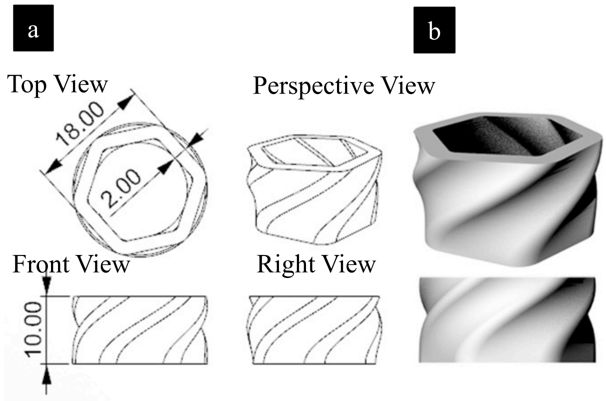

Figure 1. 3D CAD free-form rendering model

in 3D printing due to its capability to describe the surface geometry of 3D objects. The file was then sliced using Photon Workshop software (Shenzen Anycubic Technology, China). In this process, layer thickness and exposure time parameters were set according to the experimental design. The sliced models were the input for the printing process. Once the printing was completed, the results were cleaned by using isopropyl alcohol (IPA 96%) to remove the remaining resin attached to the object. The samples were dried for 72 hours for the assessment at ambient temperature to ensure no volume shrinkage occurred.

Experimental Procedure

The experimental procedures were developed by using the Response Surface Method (RSM). The RSM uses a set of mathematical and statistical approaches to design, progress, and optimize processes when several variables affect the desired surface. The objective was to maximize or minimize the response. According to Montgomery [25], the mathematical model in the RSM is described in equation (1):

$$y = F(x_1, x_2, \dots, x_n) + \varepsilon \tag{1}$$

where, y is the response variable of x_n, and ε is the error, which is typically seen as a normal distribution with an average equal to zero. The Central Composite Design (CCD) is employed in the current study, which uses a center point and estimates the curvature using star points. The component's number equals twice the number of star points (2k). The distance between the design space's center point and the star points (α) will be larger than one if the distance between the center point and the factor points is the same for each factor. As a result, CCD design is often performed using five surfaces: -1, 0, +1, α, and -α. The central point of the design is zero. The design feature and the number of components determine the precise degree of α. Montgomery [25] stated that the value of α is based on the quantity of CCD design testing to preserve rotatability and is computed in Equation (2):

$$\alpha = [\text{number of factorial runs}]^{1/4} \tag{2}$$

The control factors adopted layer thickness (x_1) and exposure time (x_2) with two levels. Thus, the α value for $k = 2$ equals 1.414. The control factors and their levels as shown in Table 1 are assumed to have a significant effect on the responses, as identified based on the preliminary printing tests.

Table 1. Adopted factors and levels

Factors		**Levels**		
		-1	**0**	**+1**
x_1	Layer Thickness (mm)	0.060	0.070	0.080
x_2	Exposure Time (s)	6	7	8

The response of dimensional accuracy was represented by height error (y_1) and thickness error (y_2) derived from the dimensional measurements. The height and thickness measurements were preferred to perform for free-form objects. The thickness of the objects was measured at the hexagonal end of the printed objects. The measurement of the object diameter was not included due to its wavy and irregular shape characteristics. The measurements were conducted by using a digital micro-caliper (±0.001 mm). The dimensional error (d) for height and thickness were calculated using equation (3), where d_1 and d_2 are actual and measured dimensions, respectively. The smaller the percentage of error obtained, the more accurate the dimension of the samples produced by the printer.

$$d = \left|\frac{d_1+d_2}{d_2}\right| \tag{3}$$

The irregular wavy shapes between the concave and the convex of the object's wall would result differently for each point of measurement. Therefore, the surface finish was evaluated qualitatively by visual observation using a digital microscope with a maximum magnificent of 1600x. Finally, analysis of variance (ANOVA) was employed to confirm the relevance of the developed model and its various terms. ANOVA is suitable for studying the influence of different factors or parameters on a particular outcome or response variable in 3D printing. The significant factors and their interactions can be identified, which can then be optimized to achieve desired outcomes in 3D printing [26]. In addition, the coefficient of determination (R^2) and its adjusted value is used to determine a model's validity.

RESULT AND DISCUSSION

Surface Finish

The 3D printing process was successful in producing a total of 13 free-form objects based on the predetermined number of experimental runs conducted using CCD method. As shown in Figure 2, the print results were evaluated for their surface finish using a digital microscope. The height and thickness of the objects were subsequently evaluated by dimensional measurements using a digital micro caliper to obtain their dimensional errors. The evaluation of surface finish utilizing a digital microscope indicates a thorough approach in assessing the visual appearance and integrity of the fabricated objects. Figure 3 displays close-up visual representations of specific regions that have been assessed on each specimen. Wavy scratches are visible from the layer marks on the entire surface of the object. The top-bottom surface of the object displays the dots on the entire area. It occurs due to the LCD screen resolution, which reflects the 2D slice image of the printed object to the resins. A higher-resolution LCD screen could improve the surface quality of the printed object because the distance between the dots is closer [27], [28]. To increase the quality of the surface finish can be treated by mechanical and chemical post-processing [29]. Polishing is an alternative mechanical process to increase surface quality by removing the wavy edges. Solvents such as acetone, ester, and chloride can improve surface quality by dissolving rough surfaces [30].

Figure 2. The 3D printed models observed by a digital microscope (a) and measured by a digital micro calliper

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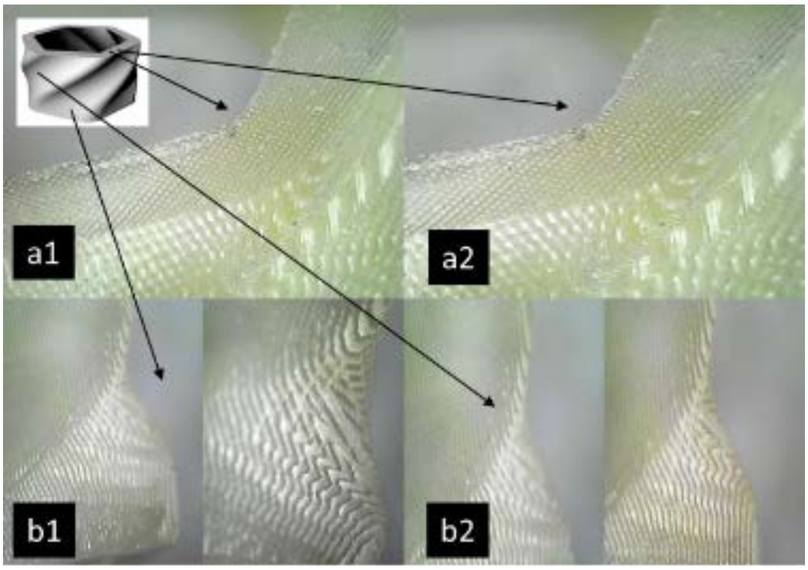

Figure 3. Surface finish of the edges and sides of the printed object

The surface quality resulting from the screen resolution of the DLP printer is also observed in the study by Barone et al. [31] and in the fabrication of orthodontic prostheses, wherein surface irregularities are still present. Nevertheless, our printed model does not show any signs of uncured resin, unlike what was observed in Barone's study. Similar results were also found in Dikova et al. [29].

Dimensional Accuracy

The results of the height and thickness errors measurements are given in Table 2. The slightest height error was given by experiment #12 with an error value of 0.001. In comparison, the highest height error was attained in an experiment #1 with an error value of 0.033. It is also found that experiment #5 has a reasonably high error with a value of 0.32. The slightest thickness error was given by experiment #12 with a value of 0.002. In comparison, the most significant error was found in an experiment #1 with an error value of 0.160. Experiment #12 has the same central point parameter setting on layer thickness and exposure time as experiment #9, #10, #11, and #13. But the error response in one of the experiments differs significantly from the others, ANOVA can help identify whether this difference is

Table 2. The results of dimensional measurements and defect observations

No.	Factors		Response	
	Layer thickness (x_1)	Exposure time (x_2)	Height error (y_1)	Thickness error (y_2)
1	-1	-1	0.033	0.160
2	1	-1	0.013	0.014
3	-1	1	0.028	0.054
4	1	1	0.017	0.018
5	-1.414	0	0.032	0.140
6	1.414	0	0.012	0.004
7	0	-1.414	0.028	0.074
8	0	1.414	0.010	0.022
9	0	0	0.013	0.037
10	0	0	0.012	0.018
11	0	0	0.012	0.014
12	0	0	0.001	0.002
13	0	0	0.011	0.011

statistically significant or simply due to random variation. Experiment #1 has a lower-level parameter setting on the two factors influencing the printed objects' dimensional accuracy.

Equations (4) and (5) represent the obtained polynomial regression which correlates the response to the coded independent variables, including layer thickness (x_1) and exposure time (x_2). In these equations, height error and thickness error (y) represent the predicted value of the dependent variable, layer thickness (x_1) and exposure time (x_2) represent the independent variables, and the numbers are the coefficients that determine the shape of the polynomial curve. The degree of the polynomial determines the flexibility of the curve in fitting the data. By estimating the coefficients, the best-fitting polynomial equation can be found that describes the relationship between x (layer thickness, exposure time) and y (height error, thickness error).

$$\mathrm{H_{error}} = 0.00966 - 0.00748x_1 - 0.00330x_2 + 0.00653x_1 * x_1 + 0.00528x_2 * x_2 + 0.00225x_1 * x_2 \quad (4)$$

$$\mathrm{T_{error}} = 0.01630 - 0.04677x_1 - 0.02188x_2 + 0.02804x_1 * x_1 + 0.01616x_2 * x_2 + 0.02737x_1 * x_2 \quad (5)$$

The ANOVA in Table 3 confirmed the model's reliability for height error. The P-value of the model is 0.008 (<0.05), which approves that the model is statistically significant. The model's lack of fit value is 0.418, the coefficient of determination R^2 was 85.10%, and its adjusted value of R^2 was 74.46%, demonstrating that the model is well fitted on the experimental data. The results show that this model can adequately estimate the height error of the printed free-form models. Moreover, the linear terms of layer thickness are highly significant (p = 0.004), but the exposure time does not significantly affect the height error (p = 0.103). The quadratic layer thickness and exposure time show a significant effect on the measured response (p<0.05), while the interaction between both parameters is not significant (p > 0.05).

Similar results were found in ANOVA for the thickness error investigation as exhibited in Table 4. The results confirmed the model's reliability. The P-value of the model is <0.05, which means that the model is statistically significant. The coefficient of determination R^2 and its modified values are 97.60% and 95.88%, respectively, indicating that the model fits well with the experimental data. The lack of fit error is 0.872, which concludes that it supports for adequacy of the fitted model. In addition, the linear terms of layer thickness and exposure time are

Table 3. ANOVA for height error

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	0.000991	0.000198	8	0.008
Linear	2	0.000535	0.000267	10.79	0.007
Layer Thickness	1	0.000447	0.000447	18.06	0.004
Exposure Time	1	0.000087	0.000087	3.52	0.103
Square	2	0.000436	0.000218	8.79	0.012
Layer Thickness*Layer Thickness	1	0.000297	0.000297	11.98	0.011
Exposure Time*Exposure Time	1	0.000194	0.000194	7.84	0.027
2-Way Interaction	1	0.00002	0.00002	0.82	0.396
Layer Thickness*Exposure Time	1	0.00002	0.00002	0.82	0.396
Error	7	0.000173	0.000025		
Lack-of-Fit	3	0.000082	0.000027	1.19	0.418
Pure Error	4	0.000091	0.000023		
Total	12	0.001164			

Model Summary:
S=0.0049775 R-sq=85.10% R-sq(adj)=74.46%

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Table 4. ANOVA for the thickness error

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	0.030899	0.00618	56.91	0.000
Linear	2	0.021326	0.010663	98.2	0.000
Layer Thickness	1	0.017496	0.017496	161.14	0.000
Exposure Time	1	0.00383	0.00383	35.27	0.001
Square	2	0.006575	0.003288	30.28	0.000
Layer Thickness*Layer Thickness	1	0.005469	0.005469	50.36	0.000
Exposure Time*Exposure Time	1	0.001817	0.001817	16.74	0.005
2-Way Interaction	1	0.002998	0.002998	27.61	0.001
Layer Thickness*Exposure Time	1	0.002998	0.002998	27.61	0.001
Error	7	0.00076	0.000109		
Lack-of-Fit	3	0.000111	0.000037	0.23	0.872
Pure Error	4	0.000649	0.000162		
Total	12	0.031659			

Model Summary
S=0.0104202 R-sq=97.60% R-sq(ad)=95.88%

highly significant ($p < 0.05$). Quadratic layer thickness and exposure time significantly affect the thickness response ($p < 0.05$). The interaction between layer thickness and exposure time parameters is also significant ($p < 0.05$).

Effect of Factors

Figure 4 (a) shows the main effect plot for height error (y_1) as the effect of the layer thickness (x_1) and the exposure time (x_2). It shows parabola plots which are the vertex point of warping deformation at y depending on the value of the factors. The lowest value of the height error is between 0.070 and 0.080 mm for the layer thickness and between 7 to 8 sec for the exposure time factor. The main effect plot for thickness error (y_2), as shown in Figure 4 (b), exhibits

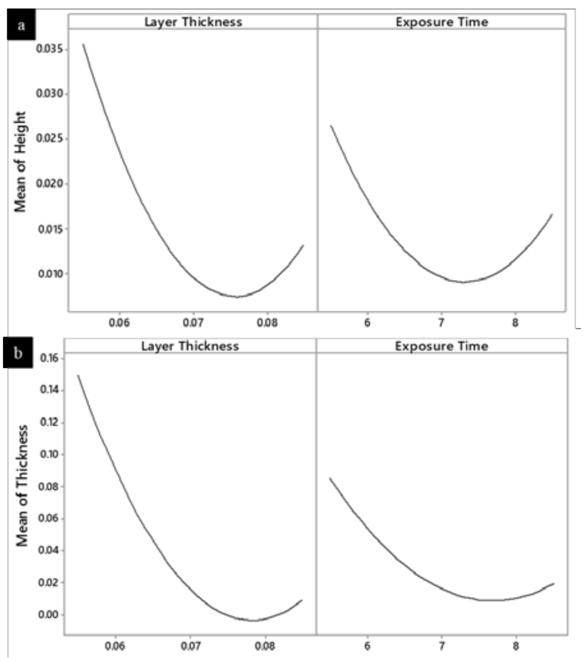

Figure 4. Main effect of layer thickness and exposure time: a) on the height error; b) on thickness error.

a parabola plot, where the lowest value of the thickness error on each factor is around 0.080 mm for the layer thickness and 8 sec for the exposure time.

The Response Surface Methodology (RSM) also describes a combination of parameters for a particular response through the surface and contour plots. The contours of the surface plots in Figure 5a and 5b illustrate the effect of changes in the independent variables of layer thickness and exposure time affecting changes in the dependent variables, i.e., height error and thickness error in the printed models, respectively. Figure 5a shows the contour plot of the height error (y_1) corner, which responded to the factors. This contour shows the best minimum warping deformation value in the middle of the green-colored ellipse by comparing the relationship between layer thickness and exposure time. As referred to in the plot of layer thickness and exposure time, the most remarkable result of warping deformation is between 7.0 to 7.5 sec exposure time and 0.075 mm of layer thickness. Figure 5c and 5d show the surface plots that illustrate the interactive influence of independent layer thickness and exposure time variables on the height and thickness errors. Figure 5c and 5d demonstrate that both layer thickness and exposure time retain their negative and positive effect on the measured errors. Both figures also exhibit the interactive effects of layer thickness and exposure time. The impacts of layer thickness and exposure time are similar to those in Figure 5a and 5b. The outcomes of our investigation have clearly demonstrated that two dominant factors exert profound influence over the attainment of superior surface quality and dimensional accuracy in 3D printing: layer thickness and exposure time parameters. This aligns seamlessly with existing literature, reaffirming the crucial roles these parameters play in the overall quality of 3D printed objects.

In line with our findings, several prior studies have found the critical significance of these parameters. For instance, Dikova et al. [29] conducted a comparative study involving the production of polymeric dental bridges using 3D printers. In their investigation, they employed a uniform layer thickness setting of 0.05 mm. Their results revealed that a DLP printer outperformed an FDM printer in terms of dimensional accuracy and surface roughness when

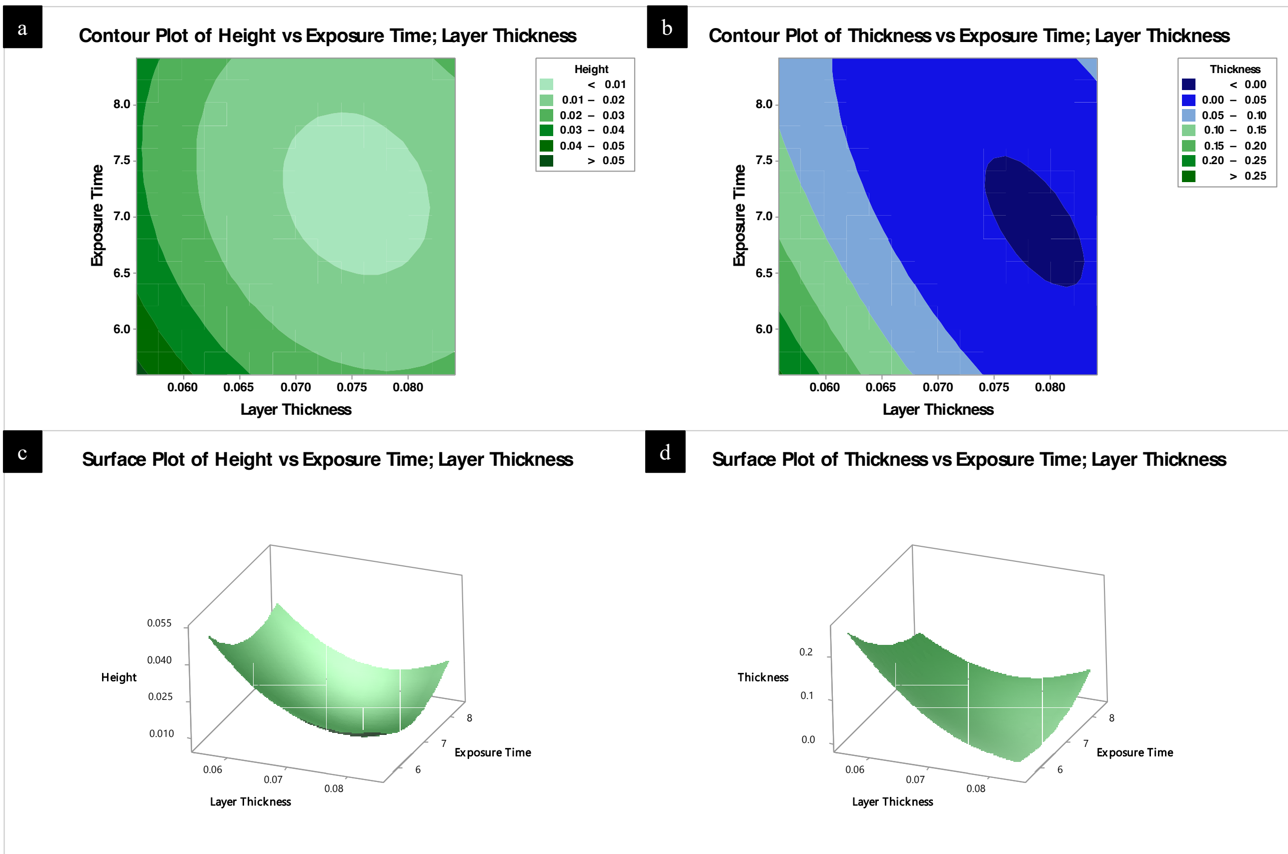

Figure 5. Result of the interaction between exposure time and layer thickness on: a) and c) height accuracy; b) and c) thickness accuracy

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utilizing these specific parameters. Similarly, Zhang et al. [32] conducted a study focused on 3D printing dental models via the DLP technique. They pinpointed that optimal printing accuracy was achieved by configuring the layer thickness to 50μm. Interestingly, they also observed an enhancement in printing speed when the layer thickness was set at 100μm. However, it is important that their study highlighted the nuanced nature of these parameter optimizations. They emphasized that while parameter adjustments can lead to improvements in printing accuracy, the evaluation of various printer brands and distinct printing technologies is imperative to attain precise accuracy levels for the intended printed object [33].

In summation, our research findings, coupled with the corroborative evidence from earlier studies such as those conducted by Dikova et al. [29] and Zhang et al. [32], collectively highlight the essential roles of layer thickness and exposure time parameters in determining the surface quality and dimensional accuracy of 3D printed objects. Furthermore, they highlight the importance of systematic evaluations in the context of different printer technologies and brands to ensure the accuracy and reliability of the final printed products.

Optimization

Through statistical analysis employing Response Surface Methodology (RSM), our investigation has yielded conclusive findings regarding the identification of optimal parameters within the 3D free-form object printing process. These optimized parameters were determined using equation (4) and (5) to yield the most favorable results in terms of minimizing errors in both the thickness and height of 3D printed. In this process, different combinations of parameter values were tested and evaluated to find the set of parameters that yield the best performance or minimize a specific metric. The optimal parameters of layer thickness and exposure time is shown in Figure 6. Specifically, the key parameters identified for optimal performance were a layer thickness of 0.0753 mm and an exposure time of 7.2143 seconds. The model performance was measured on the validation set with the results as shown in Figure 7.

This outcome allows reflective implications for the field of 3D printing, as it emphasizes the precision and accuracy that can be achieved through careful parameter selection. The layer thickness and exposure time parameters identified as optimal not only contribute to the reduction of errors but also enhance the overall quality and reliability of the 3D printing process. These findings provide valuable guidance to practitioners and researchers alike, offering a concrete framework for achieving superior results in 3D object printing applications. Moreover, it is important to note that the use of Response Surface Methodology in this study represents a robust and systematic approach to parameter optimization, lending further credibility to the validity of our conclusions. By leveraging the power of statistical analysis, our research not only provides specific parameter values for practitioners but also demonstrates

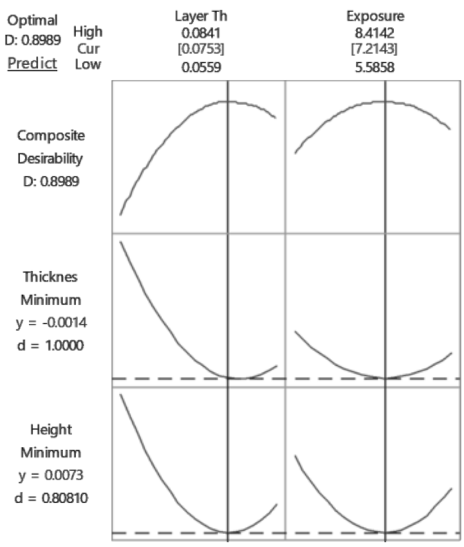

Figure 6. Optimization plot of layer thickness and exposure time

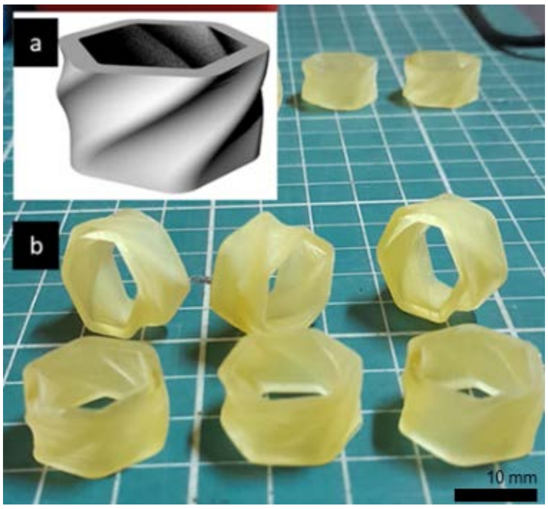

Figure 7. 3D Model: a) CAD model; b) Actual printing result

a methodological rigor that can be applied in future studies aimed at fine-tuning the 3D printing process for enhanced precision and accuracy.

The investigation conducted by Ibrahim et al. [21] found that printing parameters in determining the mechanical strength of 3D printed objects. The study reveals that a complex interplay exists between layer thickness and exposure time, exerting a discernible influence on the resultant mechanical properties of the printed specimens. The optimal configuration for achieving superior mechanical strength is highlighted, with a layer thickness of 50 μm and an exposure time of 9 seconds identified as the most favorable combination for selected 3DP machine. The observed correlation between exposure time and mechanical strength serves as a crucial factor in understanding the intricate dynamics inherent to the photopolymerization process. It highlights the necessity for a subtle equilibrium during this process. While prolonging the exposure time may indeed contribute to the augmentation of bonding between successive layers, our study discerned that an excessive duration can lead to a counterproductive impact on the mechanical performance of the final product.

This finding is consistent with previous research, further solidifying the significance of this correlation. It substantiates the assertion that exposure time stands as an essential parameter that directly influences the material properties within the 3D printing processes. This aligns seamlessly with the outcomes of an investigation conducted by Papadopoulou et al. [34], which also underscored the direct link between exposure time and the resulting mechanical properties in resin-based 3D printing. Furthermore, the work of Attaran [35] justifies remark as it emphasizes the complex interaction between exposure time and the extent of cross-linking in the context of stereolithography-based printing. This interaction, as established in their research, exerts a direct and influential effect on the mechanical behavior of the printed structures, further emphasizing the critical nature of exposure time control in optimizing the mechanical properties of 3D-printed objects. Consequently, the collective findings of our study and these prior investigations underscore the paramount importance of meticulous exposure time management in the quest for superior mechanical performance in 3D printing applications.

CONCLUSION

The results presented in this study illustrate the successful production of 13 free-form objects using the 3D printing process. The investigation also demonstrates a thorough examination of the fabricated objects' surface finish and dimensional attributes, highlighting the significance of these assessments in ensuring the quality and precision of 3D printed objects. The printed objects exhibit relatively identical surface finish results. Dimensional accuracy, represented by height and thickness errors, was optimized by the setting value of layer thickness and exposure time. In conclusion, the optimum value of the printing parameters should be set at 0.0753 mm for the layer thickness and

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7.2143 sec for the exposure time. Future study should include more varied free-form models to evaluate more printing quality and dimensional accuracy results.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest that could potentially compromise the objectivity, impartiality, or credibility of the research presented in this article.

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AUTHORS BIOGRAPHY

Farid Wajdi holds a Bachelor's and Master's degree in Industrial Design Engineering from The Hague University of Applied Sciences and Delft University of Technology, respectively. He completed his Doctorate in Mechanical Engineering from Universitas Gadjah Mada in 2021. His research interests include additive manufacturing, product innovation and management, as well as product design. Currently, he serves as a lecturer at the Department of Industrial Engineering, Universitas Serang Raya, Banten, Indonesia.

Mohd Sazli Saad, a senior lecturer at Universiti Malaysia Perlis, Malaysia, holds a Doctoral degree in Mechanical Engineering from Universiti Teknologi Malaysia. Formerly associated with the School of Manufacturing Engineering, his expertise encompasses control theory, Matlab Simulation, and optimization, reflecting a dedication to advancing engineering knowledge and practice.

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