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Optimization of Infill Density, Layer Height, and Shell Thickness to Achieve Maximum Bending Strength and Minimum Printing Time of PLA 3D Printed Part

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Abstract

3D printing has advantages in making customized products, such as leg prosthetics. One of the required properties of 3D-printed leg prosthetics is their resistance to bending stress. Based on the literature review, the influence of the interaction among layer height, infill density, and shell thickness on the bending strength and printing time has not yet been investigated or optimized. This study aims to investigate the effect and optimize the layer height, infill density, and shell thickness to achieve the maximum bending strength and minimum printing time of a Polylactic Acid 3D printed part. This research studies three independent variables: layer height, infill density, and shell thickness. The independent variables of this research are bending strength and printing time. The bending test is conducted according to the ISO 178 standard. The printed specimen is tested using the bending testing machine Tarno Grocki to measure the maximum bending load the specimen can hold. The printing time is measured by using a stopwatch. The Response Surface Method is used as an optimization method to find the value of the maximum bending strength and minimum printing time of the 3D printed part. The optimum responses are achieved using 40 % infill density, 0.3 mm layer height, and 1.6 mm shell thickness. The maximum bending strength is 118. 5129 MPa and the minimum printing time is 11.1867 minutes.

Keywords:
Optimization, 3D printing, bending strength, printing time.

1. Introduction

In 3D printing, thermoplastic materials are extruded from the nozzle and fused layer by layer to build a 3D object. One of the advantages of 3D printing is its ability to manufacture complex 3D objects without needing specific and expensive molds [1]. For that reason, 3D printing has advantages in manufacturing customized products. It can be used to manufacture various dimensions of leg prosthetics for different users at low prices [2]. In addition, it can be used for users who are still in their infancy and require more than one size of leg prosthetic as they grow every year.

One of the required properties of 3D-printed leg prosthetics is their resistance to bending stress. The bending strength of the 3D printed parts is influenced by several 3D printing parameters, including infill pattern, layer height, infill angle, infill density, shell thickness, nozzle diameter, bed temperature, extruder temperature, infill rate, and build orientation [1][3]14]. In addition, 3D printing must consider the time to manufacture the leg prosthetics. The printing time is affected by infill pattern, layer height, infill angle, infill density, shell thickness, nozzle diameter, infill rate, and build orientation.

According to previous research by Atakok, the higher the value of infill density, the higher the bending strength of the 3D-printed part [6]. An increase in infill density reduces the porosity and increases the strength of the printed part [15]. According to Chalgam *et al.*, a higher layer height value creates a 3D-printed part with higher bending strength [4]. However, another study shows that the bending strength of the 3D-printed part increases when the layer height is reduced [16]. It is presumed that the effect of the layer height on the bending strength is not linear as on the tensile strength [17]. The higher the thickness of the shell, the higher the bending strength of the 3D-printed part [7].

Based on the literature review, the influence of the interaction among layer height, infill density, and shell thickness on the bending strength and printing time has not yet been investigated. It is important to understand the effect of the interaction of the parameters and then optimize them to achieve a particular value of bending strength and reduce the manufacturing time of the 3D-printed leg prosthetics. This study aims to investigate the effect and optimize the layer height, infill density, and shell thickness to achieve the maximum bending strength and minimum printing time of the 3D printed part. The Taguchi and Response Surface are two methodologies that are commonly used to conduct this type of investigation [5] [6][10][12][18][19].

2. Materials and Methods

The material used in this study is Polylactic Acid (PLA), which is a commonly used material in 3D printing processes. The first advantage of PLA is that it is biodegradable or easily decomposed in nature as it is made of organic materials. In addition, PLA has a low melting temperature and cost compared to other filaments. However, the mechanical strength of PLA is lower compared to other materials. The PLA is bought in the form of filament as a material for the 3D printer-type Fused Filament Fabrication.

This research investigates three independent variables: layer height, infill density, and shell thickness. Each variable consists of three levels. The value of each level is shown in Table 1. The investigated value of the infill density is determined based on the median value of the possible infill density. The infill density determined the infill percentages or the amount of material used inside the printed object. The medium value, equal to 50 %, is used as the medium-level value. Then, the low and high-level values are determined by adding 10% to the medium-level value.

Table 1. The values of each independent variable level

Level Value	Low	Medium	High
Infill Density (%)	40	50	60
Layer Height (mm)	0.2	0.25	0.3
Shell Thickness (mm)	0.8	1.2	1.6

The layer height is the thickness of each extruded layer of material. Based on the works by Atakok *et al.* and Chalgam *et al.*, higher layer height increases the bending strength of the printed part [4], [6]. According to their research, the highest bending strength is achieved when using 0.3 mm layer height. Meanwhile, the standard guidelines determine that the layer height equals half of the nozzle diameter. As this research used a 3D printer with a 0.4 mm nozzle diameter, the suggested layer height is 0.2 mm. Therefore, this research used 0.2 mm, 0.25 mm, and 0.3 mm as the low, medium, and high-level values of layer height in this experiment.

The value of the shell thickness level is determined based on the nozzle diameter. The value of the shell thickness is the multiplication of the nozzle diameter. The minimum value of shell thickness equals two times the nozzle diameter. The width of the bending test specimen constrains the maximum value of the shell thickness. This research uses 0.8 mm and 1.6 mm as the minimum and maximum shell thickness, respectively. For the medium level of shell thickness, the value is 1.2 mm. The shell thickness of a 3D-printed part is measured based on how many times the nozzle deposits the filament raster to form the perimeter of the 3D-printed part. The shell thickness setting is executed before the infill density because the perimeter is printed before the inner structure of the 3D-printed part.

Table 2. The values of the printing parameter

Parameter	Value
Nozzle Diameter (mm)	0.4
Infill Pattern	Triangular
Extruder Temperature (°C)	210
Bed Temperature (°C)	60
Infill Rate (mm/s)	90
Infill Angle (°)	0

The value of other 3D printing parameters used in this research is constant and shown in Table 2. Nozzle diameter refers to the diameter of the nozzle that deposits the filament layer. The diameter of the nozzle is equal to the layer width. The infill pattern is the shape of the inner structure of the 3D-printed part. The temperature to heat the filament before it is extruded is called extruded temperature. Meanwhile, the bed temperature is a temperature set for the bed to avoid the warping of the 3D-printed part. The speed of the nozzle in printing the 3D-printed part is called the infill rate. The infill angle is the angle between the motion direction of the extruder and the X-axis of the 3D printer. The value of the printing parameters is determined based on the printer maker's recommendation and the results of the previous research. In this research, the infill pattern is selected based on research by Chada et al. [8]. The result of this research shows that the triangular infill pattern creates higher tensile and flexural strength 3D-printed parts compared to other infill patterns.

This research's independent variable or response is bending strength and printing time. The Response Surface Method is used as an optimization method to find the value of the maximum bending strength and minimum printing time of the 3D printed part. Box Behnken with two replications is used as the Response Surface Method design because it can reduce the number of experiments. According to Montgomery, desirability functions can be used as an approach method in optimizing multiple responses that have more than two control variables [20]. This method converts each response parameter (y_i) into a desirability function (d_i). The range of the desirability function value is from zero to one. The value of d_i varies depending on the target of the desired response variable. If the response variable is to be maximized, then the formula used is shown in Eq. 1.

$$d_i = \begin{cases} 0, & y < L \\ \left(\frac{y-L}{T-L}\right)^r, & L \le y \le T \\ 1, & y > T \end{cases} \quad (1)$$

Eq. 2 is used to calculate the desirability function if the response variable is to be minimized.

$$d_i = \begin{cases} 1, & y < T \\ \left(\frac{U-y}{U-T}\right)^r, & T \le y \le U \\ 0, & y > U \end{cases} \quad (2)$$

The variable y is the value of the response variable. The variable L is the lower limit. Variable T is the target to be achieved. Variable U is the upper limit, and r is the weight. The values in each response are then combined to calculate the composite desirability using Eq. 3.

$$D = (d_1 \times d_2 \times \ldots \times d_m)^{\frac{1}{m}} \quad (3)$$

Variable m is the number of responses. D values also range from zero to one. The closer the D value is to one, the closer the optimal control parameter value is to the targeted response value.

This research conducts the bending test according to the ISO 178 standard [21]. Therefore, the 3D printer is used to print bending test specimens with a length equal to 80 ± 2 mm, width equal to 10 ± 0.2 mm, and thickness or height equal to 4 ± 0.2 mm, as shown in Fig. 1. The ISO 178 standard determines the dimension tolerance.

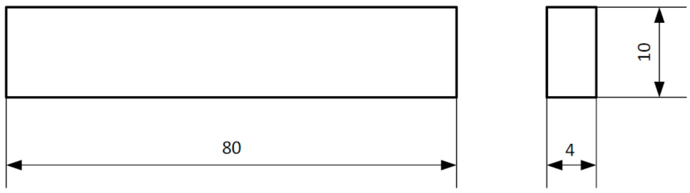

Fig. 1. Dimension of bending test specimen

Before the printing process begins, the 3D model of the bending test specimen is created using Creo 3.0 software. Then, the file is saved in STL format. The specimens are printed using the Anycubic Cobra 3D printing machine. The printing parameters are set using the Ultimaker Cura 5.1 software. The software is also used to slice the 3D model and generate the G code to move the nozzle. In total, thirty bending test specimens are printed. The printing time of each specimen is measured using a stopwatch.

Fig. 2 shows the printed specimen before the bending test is conducted. After printing, the 3D-printed part is cooled at the ambient temperature to make sure no wall deformation occurs. However, the cooling process is not investigated in this research. After that, the walls of the 3D-printed part are checked for the part shape visually. Then, the dimension of the printed specimen is measured using a caliper to ensure that the dimensions follow the standard. Then, the printed specimen is tested using the bending testing machine Tarno Grocki to measure the maximum bending load the specimen can hold. After the bending test, the fracture of the specimen is observed visually to check whether there is a large hollow that indicates the flow interruption. Finally, layer height, infill density, and shell thickness are optimized using response optimizer software to find the maximum value of bending strength and minimum value of printing time.

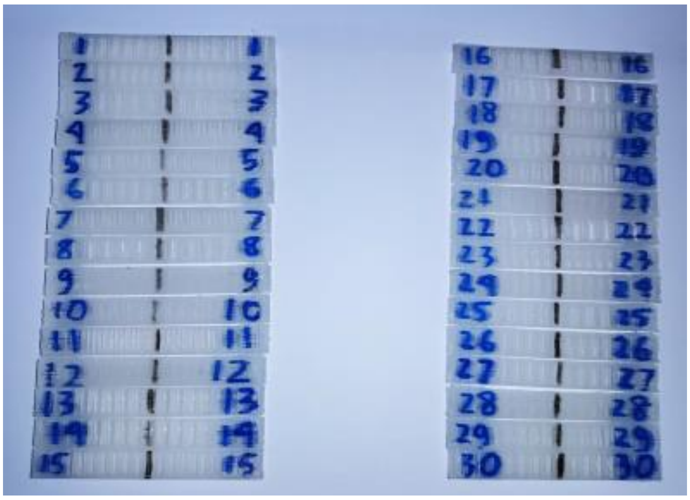

Fig. 2. Printed bending test specimen

3. Results and Discussion

The bending strength and the printing time of each 3D-printed specimen can be seen in Table 3. The result data that has been obtained is then analyzed and used to calculate the composite desirability to optimize the bending strength and the printing time using Minitab data analysis software.

Fig. 3 shows the main effect plot for bending strength. The experiment result is also analyzed by using ANOVA. Based on the analysis of variance for bending strength shown in Fig. 4, the shell thickness has the most significant influence on bending strength. Meanwhile, the infill density and layer height do not significantly affect bending strength.

As shown in Fig. 3, the increase of infill density from 40 % to 50 % increases the bending strength from 102.772 MPa to 112.260 MPa. However, the 50 % to 60 % increase in infill density does not significantly affect the bending strength. As the specimen has a thin thickness, the infill density has no significant effect on the moment inertia of the printed specimen. In contrast, decreasing the layer height increases the bending strength of the printed specimen. The decrease in the layer height creates a smaller void between the layers or between the raster. As a result, it has a higher moment of inertia that increases the moment of resistance. Finally, the shell thickness has a significant effect on the bending strength. The increase in the shell thickness from 0.8 mm to 1.2 mm significantly increases the printed specimen's bending strength from 89.2804 MPa to 127.251 MPa. It happens due to the increase in the moment of inertia of the 3D printed part as the shell thickness value increases. The highest bending strength is achieved using the highest shell thickness in the investigated range.

Table 3. The experiment results

Infill Density	Layer Height	Shell Thickness	Bending Strength (MPa)	Printing Time (Min)
40	0.2	1.2	106.60	16.7405
60	0.2	1.2	108.43	18.4425
40	0.3	1.2	99.25	11.2048
60	0.3	1.2	105.70	12.8250
40	0.25	0.8	66.57	13.8053
60	0.25	0.8	103.60	16.4313
40	0.25	1.6	148.88	13.3927
60	0.25	1.6	143.66	15.2138
50	0.2	0.8	91.10	18.1768
50	0.3	0.8	66.97	12.0678
50	0.2	1.6	123.66	18.3383
50	0.3	1.6	120.13	12.1705
50	0.25	1.2	138.98	14.3885
50	0.25	1.2	133.66	14.3453
50	0.25	1.2	103.94	14.4217
40	0.2	1.2	115.35	16.7602
60	0.2	1.2	111.79	18.4525
40	0.3	1.2	106.68	10.9815
60	0.3	1.2	101.31	12.4428
40	0.25	0.8	63.43	13.8190
60	0.25	0.8	110.37	16.4003
40	0.25	1.6	115.41	13.4473
60	0.25	1.6	111.95	15.0497
50	0.2	0.8	126.35	18.2120
50	0.3	0.8	85.84	12.0732
50	0.2	1.6	122.43	18.3312
50	0.3	1.6	131.89	11.7490
50	0.25	1.2	112.39	14.4658
50	0.25	1.2	112.01	14.4195
50	0.25	1.2	102.30	14.4563
50	0.2	1.6	122.43	16.7405

The main effect plot for printing time is shown in Fig. 5. As shown in Fig. 5, the increase in infill density from 40% to 60 % increases the required time to print the specimen from 13.7689 minutes to 15.6572 minutes. It is obvious because the 3D printer requires more time to print a denser specimen. Higher density also requires the longest required filament and increases the cost of the 3D-printed part. The increase in the layer height from 0.2 mm to 0.3 mm decreases the printing time significantly from 17.9318 minutes to 11.9393 minutes because more layers must be printed when a smaller layer height is used. Finally, shell thickness has a less significant effect on the printing time than other independent parameters. Increasing the shell thickness from 0.8 mm to 1.2 mm decreases the printing time. However, the increase from 1.2 mm to 1.6 mm increases the required printing time. Higher shell thickness generally causes longer printing time as the nozzle must move for an additional path. However, higher shell thickness reduces the infill area for a particular shell thickness and infill density. As a result, the required time to print the infill area is shortened.

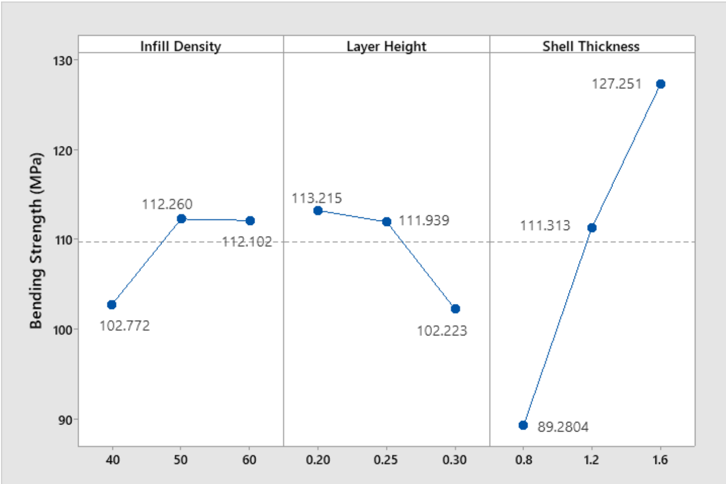

Fig. 3. Main effect plot for bending strength

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	6598.7	2199.6	9.65	0.000
Linear	3	6598.7	2199.6	9.65	0.000
Infill Density	1	348.2	348.2	1.53	0.228
Layer Height	1	483.3	483.3	2.12	0.157
Shell Thickness	1	5767.2	5767.2	25.30	0.000
Error	26	5925.9	227.9		
Lack-of-Fit	9	2691.8	299.1	1.57	0.202
Pure Error	17	3234.1	190.2		
Total	29	12524.6			

Fig. 4. ANOVA for bending strength

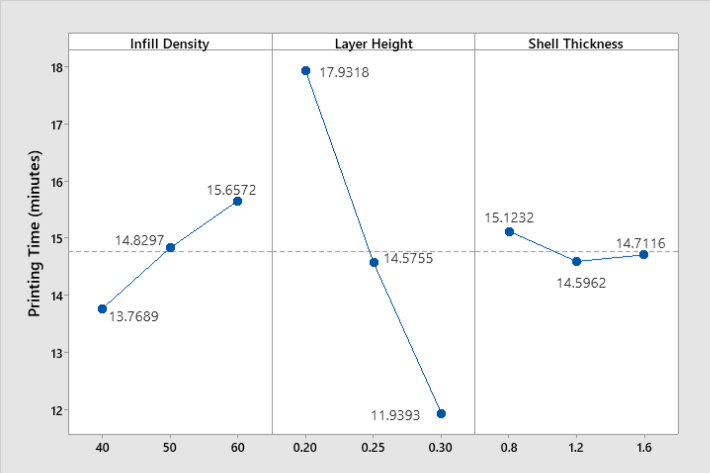

Fig. 5. Main effect plot for printing time

Fig. 6 shows the analysis of variance for printing time. The result also indicates that all three independent variables significantly influence the printing time.

The response optimizer generated by Minitab software shows that the maximum bending strength and the minimum printing time are achieved using 40 % infill density, 0.3 mm layer height, and 1.6 mm shell thickness, as depicted in Fig. 7. The maximum bending strength is 118.5129 MPa and the minimum printing time is 11.1867 minutes.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	160.846	26.808	392.71	0.000
Linear	3	158.577	52.859	774.35	0.000
Infill Density	1	14.263	14.263	208.95	0.000
Layer Height	1	143.636	143.636	2104.17	0.000
Shell Thickness	1	0.678	0.678	9.93	0.004
Square	2	1.871	0.936	13.71	0.000
Layer Height*Layer Height	1	1.101	1.101	16.13	0.001
Shell Thickness*Shell Thickness	1	0.903	0.903	13.23	0.001
2-Way Interaction	1	0.398	0.398	5.83	0.024
Infill Density*Shell Thickness	1	0.398	0.398	5.83	0.024
Error	23	1.570	0.068		
Lack-of-Fit	6	1.357	0.226	18.04	0.000
Pure Error	17	0.213	0.013		
Total	29	162.416			

Fig. 6. ANOVA for printing time

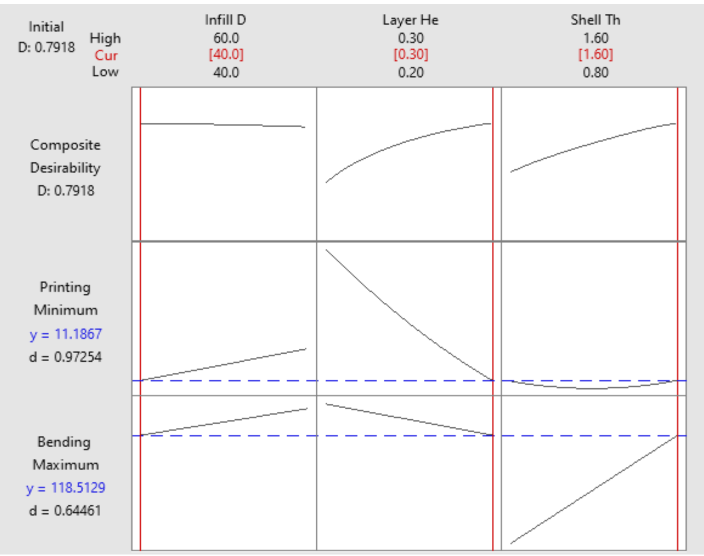

Fig. 7. Main effect plot for printing time

4. Conclusions

The bending strength increases when the infill density increases from 40 % to 50 %. Then, the bending strength value is relatively steady because more increase in the infill density has no significant effect on the moment inertia of the printed specimen. ExpMeanwhile, the influence of infill density on the printing time is linear. The increase in infill density increases the required time to print the specimen. Increasing the layer height decreases the bending strength of the printed specimen. The increase in the layer height also decreases the printing time. Finally, increasing the shell thickness increases the bending strength of the printed specimen. However, the influence of shell thickness on the printing time is not linear. Increasing the shell thickness from 0.8 mm to 1.2 mm decreases the printing time. The increase from 1.2 mm to 1.6 mm increases the required printing time. The optimum responses are achieved using 40 % infill density, 0.3 mm layer height, and 1.6 mm shell thickness. The maximum bending strength is 118.5129 MPa and the minimum printing time is 11.1867 minutes.

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