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Optimization of Fused Deposition Modeling (FDM) Machine Process Parameters for Surface Roughness of 3D Printed Products on Polylactic Acid (PLA) Filament Using the Taguchi Method

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Mochammad Willdan Rosyadi[1], Adimas Dwi Prayoga[1], Abdi Satryo Mukti[1] , Rolland Darin Khalifah Mahameru[1] and Wahyu Dwi Lestari[1]

[1]Mechanical Engineering Study Program, Faculty of Engineering, East Java Veteran National Development University, Indonesia.

Corresponding author:
Wahyu Dwi Lestari
East Java Veteran National Development University, Indonesia.
Email: revelation.dwi.tm@upnjatim.ac.id

Abstract

The surface quality of 3D printed products greatly influences the performance and aesthetics of the final product. Polyalactid Acid (PLA) is a material commonly used in 3D printing manufacturing because it is environmentally friendly and easy to use. However, the roughness of the printed surface is often a challenge that needs to be overcome to improve product quality. This research aims to optimize surface roughness in the 3D printing process using PLA material by applying the Taguchi method. The 3D printing parameters used in this research are nozzle temperature, infill density, printing speed, layer thickness, infill pattern, and orientation with each parameter having three levels. The research results show thatThe optimal parameter combination that produces the lowest surface roughness is nozzle temperature at level 2, infill density at level 3, printing speed at level 3, layer thickness at level 3, infill pattern at level 3, and orientation at level 3. The use of the Taguchi method also shows that the combination of printing process parameters is the factor that most influences the quality of the printed surface. With this optimization, it is hoped that it can improve the quality of 3D printed products and expand the application of PLA materials in various industries.

Keywords: *3D Printing, polylactic acid (PLA), surface roughness, Taguchi, Optimization.*

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INTRODUCTION

3D printing, often called additive manufacturing technology, has experienced rapid development in the last few decades. This technology enables the creation of three-dimensional objects by sequentially stacking layers of material, which provides flexibility in design and reduces material waste [1]. One of the 3D printing technologies that is often found on the market today is Fused Deposition Modeling (FDM) technology [2]. The material that is widely used in 3D printing is Polyalactid Acid (PLA), known for its biodegradable and environmentally friendly properties [3].

However, one of the main challenges in 3D printing is achieving good surface quality in the final product [4]. High surface roughness can affect not only the aesthetics but also the mechanical function of the printed component. Therefore, optimization of 3D printing process parameters to reduce surface roughness is very important [5-6]. One effective approach to optimizing the manufacturing process is to use the Taguchi method [7-9]. This method uses an efficient experimental design to determine the optimal combination of various process parameters, thereby minimizing variability and improving print quality [10-11]. The Taguchi method is particularly useful in studies involving numerous parameters, as it allows for a robust and consistent process despite the presence of uncontrolled factors (disturbing factors). Additionally, it helps in drawing conclusions regarding the response to the combination composition of factors and levels that produce an optimum response.

Previous research has applied the Taguchi method to optimize surface roughness in FDM technology. For instance, Bayu, W. K, et al [12] optimized surface roughness using layer height, printing temperature, and print speed, showing that these parameters significantly reduce surface roughness. Hasdiyansah and Sugiyarto [13] focused on layer thickness, flowrate, and orientation, concluding that layer thickness has the greatest influence on surface roughness. Andik, A. S, et al [14] used the Taguchi grey Relational analysis method to optimize dimensional accuracy and surface roughness, finding optimal parameters at a printing speed of 20 mm/s, printing temperature of 2100C, and layer height of 0.1 mm. Research conducted by Ellhafid, et al [15] examined the strength of brake linings using a surface contact analysis model. This model measured brake lining stiffness by distributing dimensional differences along the thickness of the lining, from the contact surface to the center of rotation. In other words, this research utilized surface roughness analysis to measure the strength of the brake linings. More recently, Djoko Kuswanto et al. [16] studied the modeling of prostheses for amputee patients using 3D printing technology, analyzing the structural strength to ensure optimal performance under specific load conditions.

In contrast to these studies, our research aims to optimize surface roughness of 3D printed products using PLA material by applying a broader range of parameters within the Taguchi method framework. Our study investigates six process parameters: nozzle temperature, infill density, printing speed, layer thickness, infill pattern, and orientation, each with three levels. This comprehensive approach allows us to identify the optimal combination of parameters to achieve the lowest surface roughness, thus potentially offering a more refined and holistic optimization compared to previous studies that focused on fewer parameters.

By expanding the scope of parameters considered, this research contributes to a more detailed understanding of the interaction between various 3D printing process parameters and their collective impact on surface roughness. It provides a valuable reference for practitioners and researchers in the field of additive manufacturing, aiming to enhance the quality of 3D printed products and broaden the application of PLA materials across various industries.

METHODS AND ANALYSIS

This research aims to optimize surface roughness in 3D printing manufacturing using Polyalactid Acid (PLA) material by applying the Taguchi method. The research method used consists of several stages, namely preparation of materials and tools, experimental design, implementation of experiments, data analysis, and validation of results.

Material Preparation

The material used in this research is Polyalactid Acid (PLA) with a filament diameter of 1.75 mm. The 3D printer used is the FDM (Fused Deposition Modeling) type with the FlashForg Guider II brand accompanied by Flashprint slicing software. The 3D printing machine and materials used in this research are shown in Figure 1(a-b).

Experimental Design

The experimental design in the research uses the Taguchi method with the help of Minitab 19 software. The number of process parameters or printing factors is 6 factors with each factor consisting of 3 (three) levels. The experimental parameters can be seen in Table 1. Based on these process parameters, the experimental design uses an orthogonal array L27 (36) which allows research to be carried out with 27 experiments representing a combination of various levels of each parameter. Table 2 shows the experimental design of this study.

a. b.

Figure 1. a) FlashForge Gider II 3D Printing Machine and b) PLA Filament

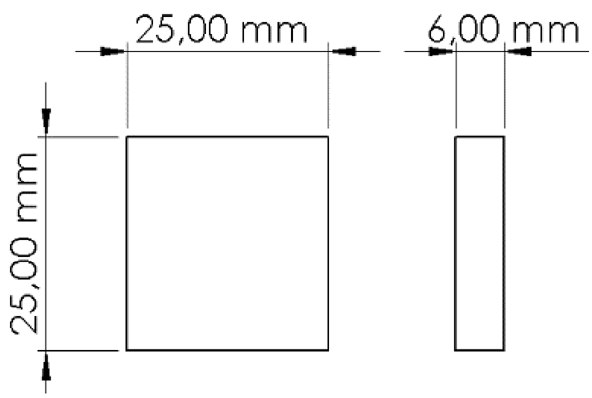

Figure 2. Sample dimensions

Table 1. Taguchi Method Table

No.	Process Parameters	Levels		
		1	**2**	**3**
1	Nozzle Temperature	190°C	200°C	210°C
2	Infill Density	80%	90%	100%
3	Printing Speed	70mm/s	80mm/s	90mm/s
4	Layer Thickness	0.15	0.2	0.25
5	Infill Pattern	Line	Triangles	Hexagons
6	Orientation	0°	15°	30°

Table 2. Experimental Design Table

No	Nozzle Temperature	Infill Density	Printing Speed	Layer Thickness	Infill Pattern	Orientation
1	190	80	70	0.15	Line	0
2	190	80	70	0.15	Triangles	15
3	190	80	70	0.15	Hexagons	30
4	190	90	80	0.2	Line	0
5	190	90	80	0.2	Triangles	15
6	190	90	80	0.2	Hexagons	30
7	190	100	90	0.25	Line	0
8	190	100	90	0.25	Triangles	15
9	190	100	90	0.25	Hexagons	30
10	200	80	80	0.25	Line	15
11	200	80	80	0.25	Triangles	30
12	200	80	80	0.25	Hexagons	0
13	200	90	90	0.15	Line	15
14	200	90	90	0.15	Triangles	30
15	200	90	90	0.15	Hexagons	0
16	200	100	70	0.2	Line	15
17	200	100	70	0.2	Hexagons	30
18	200	100	70	0.2	Hexagons	0
19	210	80	90	0.2	Line	30
20	210	80	90	0.2	Triangles	0
21	210	80	90	0.2	Hexagons	15
22	210	90	70	0.25	Line	30
23	210	90	70	0.25	Triangles	0
24	210	90	70	0.25	Hexagons	15
25	210	100	80	0.15	Line	30
26	210	100	80	0.15	Triangles	0
27	210	100	80	0.15	Hexagons	15

Implementation of Experiments

The experiment was carried out by starting with creating a sample design. The sample dimensions in this study are shown in Figure 2. Next, the CAD design was entered into the slicing software to set the parameters according to the experimental design that had been prepared. Each parameter combination was run three times to reduce variability and increase the accuracy of the results. After the printing process is complete, the surface roughness of each sample is measured using a profilometer with a Ra (Roughness average) standard. The specifications of the surface roughness tool are detailed in the Table 3.

Data analysis

Surface roughness data was analyzed using analysis of variance (ANOVA) to determine the significant influence of each parameter on surface roughness. The analysis results are used to determine the optimal parameter combination that produces the lowest surface roughness.

Validation of Results

The optimal parameter combination was tested again by running several additional experiments to validate the optimization results. Surface roughness results from validation experiments were compared with results from preliminary experiments to ensure reliability and consistency.

Table 3. Surface Roughness Tool Specifications

Specifications	Information
Brand	AMTAST SRT-6210
Displays	4 digits, 10 mm LCD, with blue backlight
Parameter	Ra, Rz, Rq, Rt
Measuring Range	Ra,Rq:0.005-16.00um/0.020-629.9uinch; Rz,Rt:0.020-160.0um/0.078-6299uinch
Accuracy	+ -10 %
Fluctuation	Not more than 6%
Censorship	Principle Test: type of Inductance; Pin Probe Radius: 5μm; Probe Pin Material: Diamond; Dynamo – Probe measurements: 4mN (0.4gf); Probe Angle: 90 ° ; Vertical Radius of Guiding Head: 48mm
Maximum Driving Stroke	17.5mm/0.7inch
Cutt Off Length	0.25mm / 0.8mm / 2.5mm optional
Fabrication	Made In China

Figure 3. Surface roughness measuring tool

RESULTS AND DISCUSSIONS

After running 27 experiments with parameter combinations determined by the L27 orthogonal array, the surface roughness (Ra) data of each sample was recorded and analyzed. The surface roughness test for each experiment was repeated three (3) times and then the average was taken. The results of surface roughness measurements from 27 parameter combinations are presented in Table 3. Next, Analysis of Variance (ANOVA) was carried out to determine the effect of each parameter on surface roughness. The results of the ANOVA are shown in Table 4.

Based on the ANOVA analysis table in Table 4, it can be seen that the nozzle temperature and printing speed parameters have a significant effect on surface roughness. The table for the S/N ratio of each parameter is F(0.05;2;14) = 3.7388918. The nozzle temperature parameter provides a contribution percentage of 97.528%, infill density of 46.602%, printing speed of 74.267%, layer thickness of 10.759%, infill pattern of 8.720%, and orientation of 2.855%.

The optimal parameters for surface roughness response in this study are shown in the S/N ratio table in Table 5. Based on the table it can be seen that the most optimal para-

Table 4. Roughness Test Results

No	Nozzle Tempe-rature	Infill Density	Printing Speed	Layer Thick-ness	Infill Pattern	Orien-tation	Surface Rough-ness (μm)	SN Ratio
1	190	80	70	0.15	Line	0	2.70400	-8.6401
2	190	80	70	0.15	Triangles	15	2.73867	-8.7508
3	190	80	70	0.15	Hexagons	30	1.18967	-1.5085
4	190	90	80	0.2	Line	0	2.59067	-8.2682
5	190	90	80	0.2	Triangles	15	5.63800	-15.0225
6	190	90	80	0.2	Hexagons	30	4.77200	-13.5740
7	190	100	90	0.25	Line	0	3.41700	-10.6729
8	190	100	90	0.25	Triangles	15	6.26800	-15.9426
9	190	100	90	0.25	Hexagons	30	8.01967	-18.0831
10	200	80	80	0.25	Line	15	4.17733	-12.4180
11	200	80	80	0.25	Triangles	30	5.45467	-14.7354
12	200	80	80	0.25	Hexagons	0	7.18333	-17.1265
13	200	90	90	0.15	Line	15	6.97267	-16.8680
14	200	90	90	0.15	Triangles	30	8.10667	-18.1768
15	200	90	90	0.15	Hexagons	0	6.10767	-15.7175
16	200	100	70	0.2	Line	15	5.08233	-14.1213
17	200	100	70	0.2	Hexagons	30	5.08767	-14.1304
18	200	100	70	0.2	Hexagons	0	6.61467	-16.4102
19	210	80	90	0.2	Line	30	7.10767	-17.0345
20	210	80	90	0.2	Triangles	0	5.24633	-14.3971
21	210	80	90	0.2	Hexagons	15	4.77967	-13.5880
22	210	90	70	0.25	Line	30	4.16800	-12.3986
23	210	90	70	0.25	Triangles	0	5.53200	-14.8576
24	210	90	70	0.25	Hexagons	15	4.82067	-13.6621
25	210	100	80	0.15	Line	30	7.31200	-17.2807
26	210	100	80	0.15	Triangles	0	5.09500	-14.1429
27	210	100	80	0.15	Hexagons	15	5.91467	-15.4386

Table 5. ANOVA

Source	DF	Seq SS	Contribution	Adj MS	F	P
nozzle temperature	2	97,528	97,528	48,764	6.24	0.012
infill density	2	46,602	46,602	23,301	2.98	0.083
printing speed	2	74,267	74,267	37,133	4.75	0.027
layer thickness	2	10,759	10,759	5,380	0.69	0.518
infill pattern	2	8,720	8,720	4,360	0.56	0.584
orientation	2	2,855	2,855	1,428	0.18	0.835
Residual Error	14	109,331	109,331	7,809		
Total	26	350,061				

Table 6. Optimal Parameters Table

Levels	Nozzle temperature	infill density	Printing speed	Layer thickness	Infill pattern	orientation
1	4,149	4,509	4,215	5,127	4,837	4,943
2	6,087	5,412	5,349	5,213	5,463	5,155
3	5,553	5,868	6,225	5,449	5,489	5,691
Delta	1,939	1,359	2,010	0.322	0.652	0.747
Rank	2	3	1	6	5	4

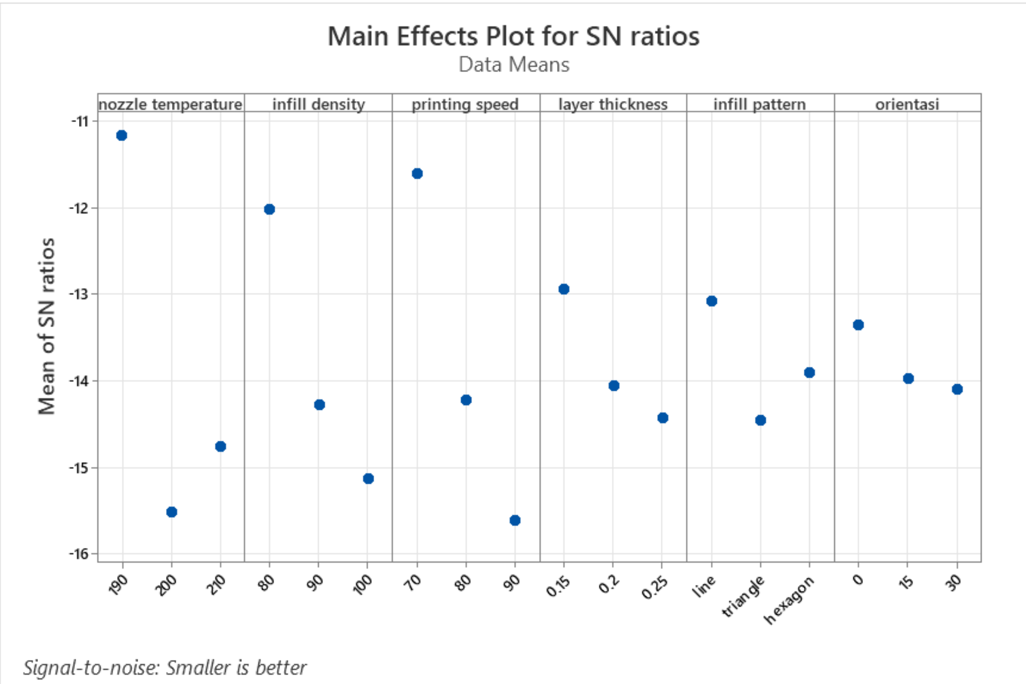

Figure 5. Graph of Optimal Levels of Roughness Response

meters are printing speed followed by nozzle temperature, infill density, orientation, infill pattern and layer thickness. Furthermore, the optimal process parameters to improve the quality of surface roughness on PLA material through the 3D printing manufacturing process occur if the nozzle temperature is set at level 2, infill density at level 3, printing speed at level 3, layer thickness at level 3, infill pattern at level 3, and orientation at level 3 (Figure 5).

Based on the graph in Figure 5, it can be seen that the optimal parameters to obtain minimum surface roughness if the 3D printing process is set at nozzle temperature at level 2, infill density at level 3, printing speed at level 3, layer thickness at level 3, infill pattern at level 3, and orientation at level 3. The next step is to calculate the confidence interval for the prediction experiment using the following calculations.

$$\mu_{prediction} = y_m + (A_1 - y_m) + (B_1 - y_m) + (C_1 - y_m) + (D_1 - y_m) + (E_1 - y_m) + (F_1 - y_m)$$

$$\mu_{\text{prediction}} = -5{,}26266 + (-4{,}149 + 5{,}26266) + (-4{,}509 + 5{,}26266) + (-4{,}215 + 5{,}26266) + (-5{,}127 + 5{,}26266) + (-4{,}837 + 5{,}26266) + (-4{,}493 + 5{,}26266)$$

$$\mu_{prediction} = -1.0167$$

The confidence interval of the predicted mean S/N ratio using a 95% CI can be calculated as follows.

$$n_{eff} = \frac{27\times3}{1+(2\times6)} = \frac{81}{13}$$

$$CI_p = \sqrt{\frac{3.7388918\times7{,}089}{\frac{81}{13}}} = 2{,}037$$

Where the n_{eff} is S/N Trust Ratio and CI_p is CI Prediction, so that :

$$-1{,}0167\text{-}2{,}037 \leq \mu_{\text{prediction}} \leq -1{,}0167 + 2{,}037$$
$$-3{,}0537 \leq \mu_{\text{prediction}} \leq 1.0203$$

The next stage is optimizing parameter variations to carry out confirmation tests by printing test specimens and measuring their surface roughness. In addition, the results of roughness measurements can be assessed as appropriate test results. The results of this test will later be used in the confirmation test for optimizing parameter variations. The table below shows the results of the confirmatory test experiments of surface roughness testing. The resulting data is in the form of average surface roughness.

The results of calculating the confidence interval for the average value of the S/N ratio at the 95% confidence level in the confirmation test are as follows.

$$n_{eff} = \frac{27\times3}{1+(2\times6)} = \frac{81}{13}$$

$$CI_k = \sqrt{3.7388918\times7{,}089\times\left[\frac{1}{\frac{81}{13}} + \frac{1}{3}\right]} = 3{,}617$$

Where n_{eff} is S/N Trust Ratio and CI_p is CI Confirm.

The results of calculating the confidence interval at the 95% confidence level for predictions are then compared with the confidence interval at the 95% confidence level for the confirmation test.

Table 7. Data Results from Confirmation Tests

Nozzle Tempe-rature	Infill Density	Printing Speed	Layer Thickness	Infill Pattern	Orien-tation	Test result	SN Ratio
190	80	70	0.15	Hexagons	30	1.18967	-1.5085
190	80	70	0.15	Hexagons	30	1.18967	-1.5085
190	80	70	0.15	Hexagons	30	1.18967	-1.5085
			Average			1.18967	1.5085

CONCLUSIONS

This research has succeeded in optimizing surface roughness in the 3D printing manufacturing process using Polylactic Acid (PLA) material by applying the Taguchi method. Based on the experimental results and data analysis, several things can be concluded as follows:

1. Parameters that have a significant effect on surface roughness are nozzle temperature and printing speed.
2. The optimal parameter combination that produces the lowest surface roughness is nozzle temperature at level 2, infill density at level 3, printing speed at level 3, layer thickness at level 3, infill pattern at level 3, and orientation at level 3.
3. Validation of the results with additional experiments shows consistent results with an average surface roughness of 1.18967 µm, proving that the Taguchi method is effective in optimizing 3D printing process parameters to reduce the surface roughness of PLA material.

Overall, this research shows that the application of the Taguchi method can significantly reduce surface roughness in the 3D printing process using PLA material, which ultimately improves the quality of the final product. Further research can be carried out to investigate the influence of other parameters and different materials in improving the quality of 3D printing. The results of this research can provide practical guidance for the additive manufacturing industry in improving the quality of 3D printing products.

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