Journal of Mechanical Engineering Science and Technology
Vol. 7, No. 2, November 2023, pp. 96-105

Study on Effect of 3D Printing Parameters on Surface Roughness and Tensile Strength Using Analysis of Variance

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Article history:
Received: 8 January 2023 / Received in revised form: 22 March 2023 / Accepted: 30 March 2023
Available online 31 July 2023

ABSTRACT

Fused deposition modeling of 3D printing is the process of making workpieces or parts by adding filaments to each layer. Some indicators of a high-quality product of 3D printing are the precisions dimensions, the surface roughness, and tensile strength. This research aims to find the parameters most affecting surface roughness and tensile strength. The research design used an experimental method with input parameters: (1) print speed (15-35 mm/s), (2) print temperature (200-210°C), (3) layer height (0.1 – 0.3 mm), (4) infill line directions (0-90°), and dependent variables were surface roughness and tensile strength. The data distribution used the L9 orthogonal array, and the statistic analysis used ANOVA. Material uses nanographite-reinforced polylactic acid (PLA) filament. The results indicate that print parameters that significantly affect surface roughness are layer height and infill line directions. The best surface roughness on the layer height parameter is 0.1 mm, and the infill line directions parameter is 90°. Based on ANOVA analysis, print speed, print temperature, and layer height do not significantly affect tensile strength, but infill line directions significantly affect tensile strength. The best tensile strength on infill line directions is 90°. The best average tensile strength with nanographite-reinforced PLA filament is 38.56 N/mm^2, with 35 m/s print speed, 205 °C print temperature, 0.1 mm layer height, and 90° infill line direction parameter. The best average surface roughness with nanographite-reinforced PLA filament is 0.66 µm, with 35 m/s print speed, 205 °C print temperature, 0.1 mm layer height, and 90° infill line direction parameter.

Keywords: *3D print, ANOVA, nanographite, polylactic acid filament, roughness, tensile strength*

I. Introduction

The flow chart of making a product generally consists of ideas, designs, prototypes, performance tests, and implementation. Prototypes aim to evaluate the products before they are implemented and manufactured in mass production. Prototypes are made in small quantities so that the additive manufacturing process is prioritized over other manufacturing processes. Additive manufacturing is efficient and effective for small amounts of products [1]. In addition, creating complex models using additive manufacturing can eliminate jigs and fixtures.

Additive manufacturing has several types, one of which is FDM (fused deposition modeling). Type FDM of additive manufacturing is the process of making workpieces or parts by adding filaments to each layer. Additive manufacture is appropriate if applied to

DOI: 10.17977/um016v7i22023p096

prototypes that make the manufacture of varied parts and small quantities. Additive manufacturing has a cheaper and more consistent process price. As an illustration, additive manufacturing can make parts cheaper than injection molding processes in the range of 4000 to 12000 parts with a production cost of 2.1 €/part, in injection molding cheaper with parts above 12000 with a production price range below 2 €/part [2].

Additive manufacturing does not require a longer process. Additive manufacturing can make a simple process so that it requires two methods (raw material and component manufacturing), compared to traditional manufacturing, which requires three methods (raw materials, part manufacturing, and assembly parts). Besides that, in making parts, it is necessary to combine several machines for complicated shapes [2]. Two hundred million users predicted in 2026, 3D printing is predicted to grow from 18% to 32% (2018 to 2026) with USD 7-23 billion to USD 51.77 billion [3].

Factors affecting the print result are the material, machine, and setting parameters. The quality of 3D print objects is affected by setting parameters, setting the distance of the reference point, and choosing a filament with the appropriate adhesion [4]. Setting parameters of 3D printing greatly affects print quality. The lower layer height has an impact on increasing tensile strength, smoothness, and dimensional accuracy of 3D print objects, but affects the long print time [5]. Some parameters like print speed (PS) and print temperature (PT) need to be tested.

Surface roughness and topography are the main parameters that indicate the accuracy of components. However, the average surface roughness (Ra) of arithmetic samples made by material extrusion varies between 9 and 40 μm, which can be categorized as poor surface roughness [6]. Layer height (LH) or thickness affects the surface quality and dimensions of the workpiece more than other parameters such as PS and PT [7]. In previous studies, researchers discussed the effect of PS, PT, and LH on surface roughness. It is necessary to show the contribution of print speed, printing temperature, layer thickness, and infill line directions to the tensile strength and surface roughness. The goal of this research is to find the parameters that most affect surface roughness and tensile strength.

II. Material and Methods

This research was an experimental study, experimental data distribution used L9 (3^3) orthogonal arrays. Statistical analysis used the analysis of variance (ANOVA). The ANOVA method was utilized to understand the percentage of contribution of each parameter. ANOVA analysis was used to find the critical factor for a specified response [8]. In this research, data distribution used L9 (3^3) orthogonal arrays because it was more cost-effective than the full factorial method [9]. Variable independent and dependent is shown in Figure 1, and the level of the dependent variable is shown in Table 1.

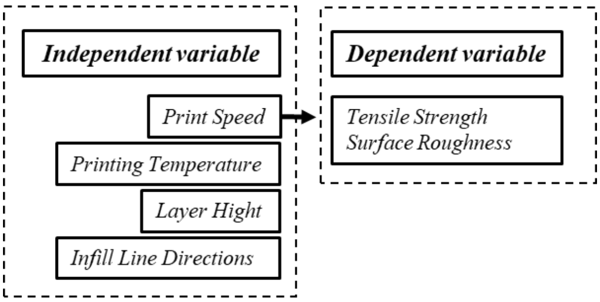


Fig. 1. Independent variables and dependent variables

Table 1. Variables and data distribution

Variables	Code	Unit	Variations		
Print Speed	PS	mm/s	15	25	35
Printing Temperature	PT	°C	200	205	210
Layer Height	LH	mm	0.1	0.2	0.3
Infill Line Directions	ILD	°	0	45	90

The object of this study was the ASTM D638 Type IV specimen with PLA material. The design of the L9 (3^4) orthogonal array with three replications as shown in Table 2.

Table 2. Design of experiment L9 orthogonal array

No	PS	PT	LH	ILD	PS	PT	LH	ILD
1	-1	-1	-1	-1	15 mm/s	200 °C	0.1 mm	0°
2	-1	0	0	0	15 mm/s	205 °C	0.2 mm	45°
3	-1	1	1	1	15 mm/s	210 °C	0.3 mm	90°
4	0	-1	0	1	25 mm/s	200 °C	0.2 mm	90°
5	0	0	1	-1	25 mm/s	205 °C	0.3 mm	0°
6	0	1	-1	0	25 mm/s	210 °C	0.1 mm	45°
7	1	-1	1	0	35 mm/s	200 °C	0.3 mm	45°
8	1	0	-1	1	35 mm/s	205 °C	0.1 mm	90°
9	1	1	0	-1	35 mm/s	210 °C	0.2 mm	0°

The study used nanographite-reinforced polylactic acid (PLA) filament with the specifications as shown in Table 3. The print process uses a 3D printer (Creality Ender 3 Prusa i3) with a diameter of a single nozzle is 0.4 mm.

Table 3. Characteristic of nanographite-reinforced PLA filament for 3D Print

Print temp. (°C)	190 – 210	Tensile strength (N/mm^2)	33.8
Bed temp. (°C)	No Heat/(60—80)	Elongation at break (%)	10.39
Density (g/cm^3)	1.09	Modulus young (N/mm^2)	3.4

The surface roughness (Ra) was measured in a Surftest SJ-310 Series (Mitutoyo, Japan), and the tensile strength test was conducted in JTM-UTS210 Computer Servo Universal Testing Machine (2T) using the standard of ASTM D638 Type IV [10] as shown in Figure 2. The statistical analysis used in this study was a three-way ANOVA (three-lane ANOVA). A three-lane ANOVA is used to test the mean differences of three or more sample groups with three independent variables and one dependent variable. In this study, ANOVA analysis used Minitab software.

The hypotheses of this study are:
H_0 = there is no difference between the average n groups.
H_1 = there is a difference between the average n groups.

The interpretation of c is:

If the p-value is less than $\alpha = 0.05$, so H_1 is accepted, or H_0 is rejected
If the p-value is more than $\alpha = 0.05$, so H_0 is accepted, or H_1 is rejected

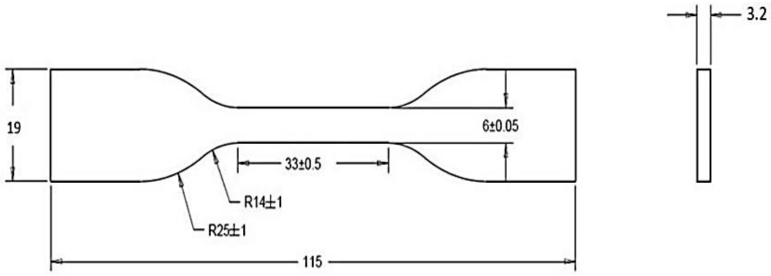


Fig. 2. Tensile test specimen ASTM D638 type IV

If the test results show H_0 (no difference), then the follow-up test (Post Hoc Test) is not carried out. On the other hand, if the test results show H_1 (there is a difference), then a further test (Post Hoc Test) must be carried out.

III. Results and Discussions

The data of roughness and tensile strength of 3D-printed product is shown in Table 4.

Table 4. Roughness and tensile strength of the 3D-printed product

Run	Roughness (Ra)			Tensile strength (N/mm^2)		
	1	2	3	1	2	3
1	3.21	6.44	4.97	31.17	26.56	22.48
2	9.78	14.09	10.63	35.71	35.39	24.37
3	3.21	2.31	2.24	31.95	27.46	31.71
4	1.60	6.24	5.08	30.29	38.69	33.87
5	18.91	12.56	18.60	30.34	25.00	26.93
6	2.01	2.34	14.91	31.35	35.92	40.99
7	18.26	10.85	22.72	24.91	20.46	28.66
8	1.09	0.52	0.36	38.26	35.58	41.84
9	7.85	26.38	33.10	32.29	26.61	32.48

Analysis of Surface Roughness

ANOVA analysis of the surface roughness of 3D-printed product is shown in Table 5.

Table 5. ANOVA analysis results for surface roughness of the 3D-printed product

Source	DF	Adj SS	Adj MS	F-Value	P-Value
PS	2	232.72	116.358	3.64	0.047
PT	2	12.47	6.237	0.19	0.825
LH	2	433.30	216.649	6.77	0.006
ILD	2	723.68	361.840	11.31	0.001
Error	18	575.93	31.996		
Total	26	1978.10			

The interpretation of data from the ANOVA results is shown in Table 6.

Table 6. Interpretation of ANOVA results for average surface roughness of the 3D-printed product

Source	P-Value	Decision	Interpretation
PS	0.047 < 0.05	H_0 is rejected	There is a difference in average surface roughness at a PS of 15; 25, and 35mm/s.
PT	0.825 > 0.05	H_0 is accepted	There is no difference in average surface roughness at PT of 200; 205, and 210°C
LH	0.006 < 0.05	H_0 is rejected	There is a difference in average surface roughness on LH of 0.1 mm, 0.2 mm, 0.3 mm
ILD	0.001 < 0.05	H_0 is rejected	There is a difference in the average surface roughness in ILD of 0°, 45°, 90°.

The analysis results in Table 6 show that the 3D printing parameter variables (PS, PT, LH, and ILD) that affect the surface roughness of 3D-printed product is the PS and LH [11] and ILD. From the summary model obtained R-Square by 70.88 %, this means that the value of the influence of PS, PT, LH, and ILD on surface topology is 70.88% while other variables influence the remaining 29.12%.

The grouping information results are shown in Table 7, and the simultant test results using the Tukey test are shown in Table 8. They show that PS of 15 mm/s, LH of 0.1 mm, and ILD of 90° have a small average value, so that is a smooth surface.

Table 7. Grouping information using the Tukey method and 95% confidence

PS					LH					ILD				
PS	N	Mean	Grouping		LH	N	Mean	Grouping		ILD	N	Mean	Grouping	
35 mm/s	9	13.46	A		0.2 mm	9	12.75	A		0	9	14.67	A	
25 mm/s	9	9.14	A	B	0.3 mm	9	12.18	A		45	9	11.73	A	
15 mm/s	9	6.32		B	0.1 mm	9	3.98		B	90	9	2.51		B

Table 8. Tukey simultaneous tests for differences means

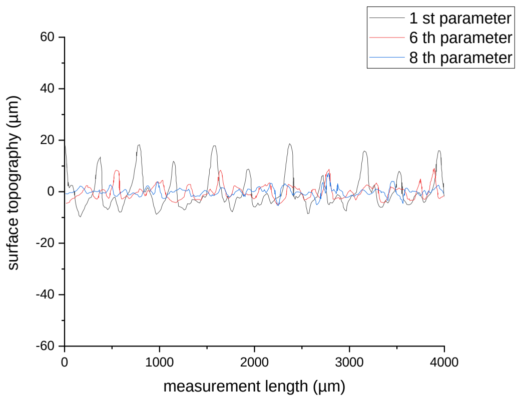
PS			LH			ILD		
Difference of levels	Difference of means	Adj P-value	Difference of levels	Difference of means	Adj P-value	Difference of levels	Difference of means	Adj P-value
25 - 15 mm/s	2.82	0.552	0.2 - 0.1 mm	8.77	0.011	45 - 0	-2.94	0.526
35 - 15 mm/s	7.14	0.039	0.3 - 0.1 mm	8.20	0.017	90 - 0	-12.15	0.001
35 - 25 mm/s	4.32	0.263	0.3 - 0.2 mm	-0.57	0.976	90 - 45	-9.22	0.008

Table 9 indicates that PS of 15 mm/s have a difference with PS of 35 mm/s; LH of 0.1 mm has a difference with LH of 0.2 mm and 0.3 mm; ILD of 90° have a difference with LH of 0° and 45°.

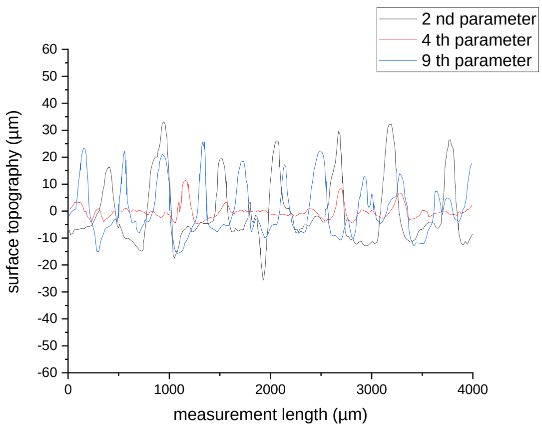
Table 9. Interprestasi data Tukey simultaneous for surface roughness of the 3D-printed product

Difference of Levels	Adjusted P-Value	Decision	Interpretation
Print Speed			
25 - 15 mm/s	0.552>0.05	H0 Accepted	there isn’t a difference between PS 25 and 15 mm/s
35 - 15 mm/s	0.039<0.05	H0 Rejected	there is a difference between PS 35 and 15 mm/s
35 - 25 mm/s	0.263>0.05	H0 Accepted	there isn’t a difference between PS 35 and 25 mm/s
Layer Height			
0.2 - 0.1 mm	0.011<0.05	H0 Rejected	there is a difference between LH 0.2 and 0.1 mm
0.3 - 0.1 mm	0.017<0.05	H0 Rejected	there is a difference between LH 0.3 and 0.1 mm
0.3 - 0.2 mm	0.976>0.05	H0 Accepted	there isn’t a difference between LH 0.3 and 0.2 mm
Infill Line Directions			
45° - 0°	0.526>0.05	H0 Accepted	there isn’t a difference between ILD 45° and 0°
90° - 0°	0.001<0.05	H0 Rejected	there is a difference between ILD 90° and 0°
90° - 45°	0.008>0.05	H0 Rejected	there is a difference between ILD 90° and 45°

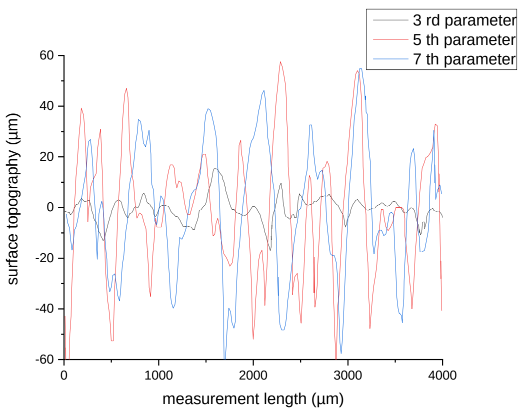
Figure 3 show the grouping of LH with topographic results.



(a)



(b)



(c)

Fig. 3. Topographic graph with LH of (a) 0.1 mm; (b) 0.2 mm; (c) 0.3 mm.

Based on Figure 3, LH of 0.1 mm has a better surface than LH of 0.2 mm and 0.3 mm. LH of 0.1 mm has a good surface because each print has a small height, so the nozzle output is also small and the result smoother. The smaller the print height, the better the results obtained, but the longer the printing time. The LH, followed by the nozzle diameter, are the process parameters that greatly influence the arithmetical mean height (Ra) [12].

Analysis of Tensile Strength

The result of ANOVA of tensile strength of the 3D-printed product is shown in Table 10.

Table 10. ANOVA analysis results for tensile strength of the 3D-printed product

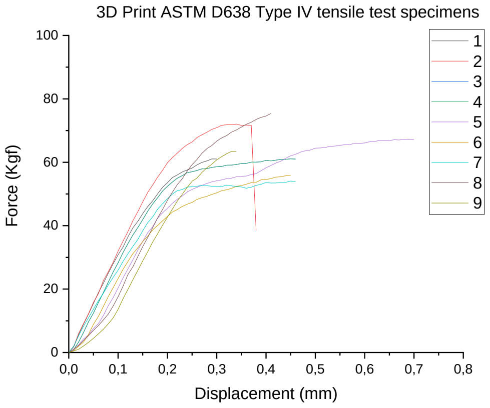
Source	DF	Adj SS	Adj MS	F-Value	P-Value
PS	2	39.32	19.66	1.16	0.337
PT	2	91.13	45.57	2.68	0.096
LH	2	193.14	96.57	5.68	0.012
ILD	2	174.10	87.05	5.12	0.017
Error	18	306.29	17.02		
Total	26	803.99			

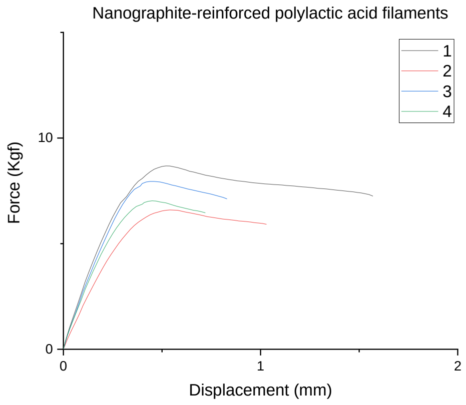
The interpretation of data from the ANOVA results is shown in Table 11. From the summary model, it is obtained R-Square by 61.90%. This means that the value of the influence of print speed (PS), print temperature (PT), layer height (LH), and infill line direction (ILD) on tensile strength (Y) is 61.90% while other variables influence the remaining 38.1%.

Table 11. Interpretation of the ANOVA analysis for tensile strength data of 3D-printed product

Source	P-Value	Decision	Interpretation
PS	0.337 > 0.05	H0 Accepted	There is no difference in tensile strength at PS of 15; 25, and 35 mm/s
PT	0.096 > 0.05	H0 Accepted	There is no difference in tensile strength at PT of 200; 205, and 210 °C
LH	0.012 < 0.05	H0 Rejected	There is a difference in tensile strength at print layer heights 0.1; 0.2, and 0.3 mm
ILD	0.017 < 0.05	H0 Rejected	There is a difference in tensile strength at print infill line directions 0°; 45° and 90°

Based on ANOVA analysis, PS and PT have no significant effect on tensile strength. Other variables influence based on the remaining R-square (38.1%). Other possible influencing variables, such as material and filament diameter, need to be investigated. Based on ANOVA Analysis, layer height (LH) and infill line direction (ILD) significantly affect tensile strength. 3D printing type FDM has the best tensile strength at the 90°-angle print (parallel to the tensile axis) and has poor tensile strength when the print angle is below 50° [13]. 3D Print of FDM makes shapes by adding layer by layer with a pattern like arranging fibers, therefore the best tensile strength is a tensile force that is parallel with the fibers.





(a) **(b)**

Fig. 4. (a) Force and displacement of the 3D-printed specimen; (b) Nanographite-reinforced PLA filament

The force and displacement graph of a 3D-printed product using ASTM D638 type IV is shown in Figure 4. The graph shows the material printed from PLA has brittle properties, different from PLA as raw material that have ductile properties. The average tensile strength of nanographite-reinforced PLA filaments is 34.705 N/mm^2. Nanographite-reinforced PLA filaments more strong than PLA filaments with 13.22 N/mm^2 [14].

The ultimate tensile strength decreases as the printing angle becomes smaller or the layer becomes thicker. This theoretical model and experimental method can also be applied to other 3D printing materials fabricated by FDM or SLA techniques [15]. The tensile test of PLA with the ASTM D638 specimen results shows that parts printed at a raster angle of 0° exhibit higher tensile strength than parts printed at a raster angle of 90° [16]. The tensile test was performed to measure the effect of different raster angles, layer height, and raster width [16].

IV. Conclusions

The four dependent variables (print speed, print temperature, layer height, and infill line direction) that have a significant effect on surface roughness are print speed, layer height, and infill line direction. From the follow-up Post Hoc Test, the most superior parameter of print speed, layer height, and infill line direction are 15 mm/s, 0.1 mm, and 90°, respectively, which indicates the highest level of surface smoothness.

Based on ANOVA analysis, print speed (PS) and print temperature (PT) have no significant effect on tensile strength. Successively the effect of prints speed (PS), print temperature (PT), layer height (LH), and infill line direction (ILD) on tensile strength, as seen from the p-value, is 0.47; 0.825; 0.006; and 0,001, respectively. In the future, this nanocomposite filament can be applied to product which needs better surface finishing.

Acknowledgment

The authors would like to appreciate the Universitas Negeri Malang, which provides the facilities to conduct the research and DRTPM through the research grant scheme PPS-PTM with contract number of 20.6.88/UN32.20.1/LT/2023.

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