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Investigation of FDM Process Parameters and their Interactions on Surface Roughness of PLA 3D Printed Parts

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Abstract. This study investigates the effect of fused deposition modeling (FDM) process parameters and their interactions on the surface roughness of 3D-printed polylactic acid (PLA) parts. The considered parameters include layer thickness, infill percentage, raster width, extrusion temperature, raster angle, and build orientation. To capture more detailed effects, build orientation was divided into orientation around the X-axis and Y-axis, while raster angle was split into the initial layer angle and the angle between successive layers, resulting in eight studied factors. A two-phase experimental approach was employed: an initial screening experiment to identify significant factors, followed by an expanded design matrix based on response surface methodology (RSM) for detailed analysis. The results revealed that layer thickness and build orientation significantly influence surface roughness, with the stair-stepping effect playing a critical role. In contrast, infill percentage and raster angle showed a non significant effect. The interactions between key parameters demonstrated notable effects on surface quality.

1. Introduction

Additive manufacturing (AM) is a revolutionary technology that builds parts from 3D digital data by adding material layer by layer [1]. AM is different from subtractive manufacturing methods, which involve the removal of material from a larger block, enabling unparalleled customization and design complexity. AM was initially employed for rapid prototyping to create non-functional models. It had been developed to create final functional parts used in various industries, including healthcare, automotive, aerospace, electronics, etc. [2–5]. Out of all AM processes, fused deposition modelling (FDM) stands out for its popularity as it operates by selectively depositing material through a nozzle. In the FDM process, models are created and transformed into stereolithography (STL) files. The slicing program then creates the necessary machine codes, which define all the printing settings. During the printing process, a thermoplastic material is heated and extruded through a nozzle in a semi-liquid condition. The nozzle travels in both the X and Y directions along a predetermined path, gradually depositing the material layer by layer onto the print bed, as illustrated in Figure 1.

Although FDM has many advantages, it faces challenges in achieving smooth surface roughness due to the stair step effect, which arises on inclined or curved surfaces, resulting in a rough surface finish. Extensive efforts have been made by researchers to address and overcome these challenges, focusing on improving surface quality through various post-processing techniques applied to the printed parts. Chemical smoothing is a frequently used technique to improve the appearance of printed components. It involves using solvents like acetone for ABS (Acrylonitrile Butadiene Styrene) or ethyl acetate for PLA to dissolve the outer layer, resulting in a smoother surface and boosting the aesthetic appeal of the items [6]. Furthermore, researchers have investigated the use of coatings and paints to enhance surface quality. Applying a thin layer of epoxy or other coating materials can fill in the gaps and provide a smoother finish, while also offering additional benefits such as increased strength and improved thermal properties [7]. Ironing is a popular post-processing method for enhancing FDM components' surfaces. Using a heated nozzle to compress and smooth the print's top layer has been tested to reduce surface roughness. The visual and tactile aspects of printed components are greatly improved by sliding the nozzle over the surface without extruding material [8,9].

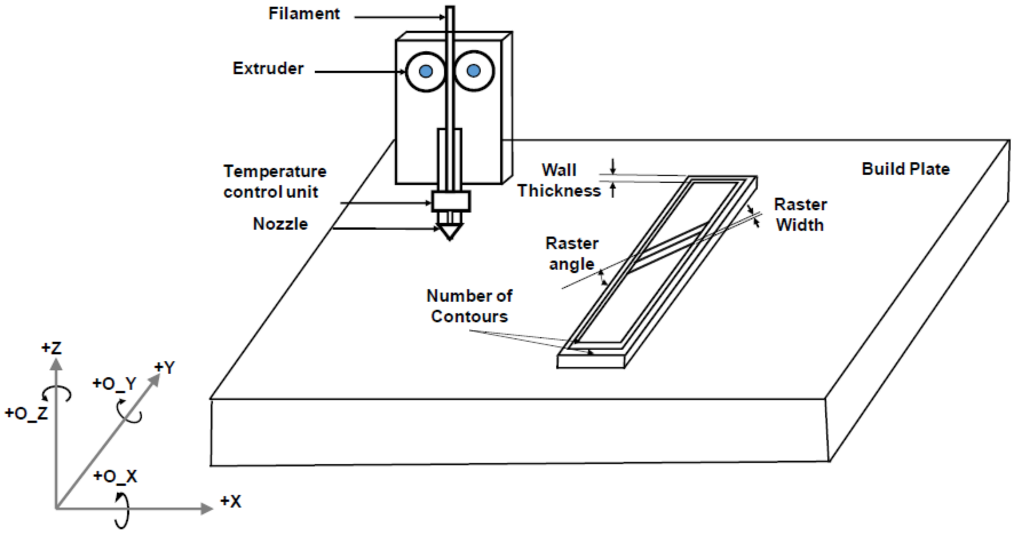

Figure 1. FDM process main components, axis of motion and Parameters

Although there have been improvements in post-processing techniques, there is still a strong focus on studying the impact of FDM process parameters on surface quality, especially for complicated printed parts and parts with large surface areas. Altering the FDM process parameters was challenging due to the large number of parameters and their impact on surface roughness. Several studies have examined how process parameters affect the surface roughness in the FDM process. Khan et al. [10] investigated the impact of machine parameters, including raster angle, raster width, air gap, and smoothing parameters, on vapor smoothing using acetone vapor. It was discovered that the air gap is the most important factor, with smoothing parameters coming in second. Furthermore, Golhin et al. [11] reviewed the influence of several FDM process parameters on surface roughness. The researchers determined that layer thickness, build orientation, print speed, nozzle diameter, and extrusion temperature were the key factors that significantly affect the quality of the surface. In another study, Vyavahare et al. [12] investigated the impact of layer thickness, wall thickness, print speed, build orientation, and extrusion temperature on surface roughness. Their research uncovered that layer thickness and build orientation were the most influential factors. They observed that as the layer thickness increased, the surface roughness also increased. Conversely, they found that as the orientation angle shifted from zero to 90 degrees, the surface roughness decreased. In their study, Ouazzani et al. [13] examined the impact of print speed, layer thickness, and extrusion temperature on surface roughness. They found that reducing layer thickness improves surface quality. They also observed that there were significant interactions between extrusion temperature and both layer thickness and print speed. However, the main effect of extrusion temperature was not found to be significant. Buj et al. [14] investigated the impact of the build orientation on surface roughness and observed that increasing build orientation led to an increase in roughness. This was attributed to the stair-stepping effect, which is in contrast to the findings of Vyavahare et al. [12] and García et al. [15] but aligns with the results reported by Caminero et al. [16]. In addition, Nugroho et al. [17] evaluated the impact of nozzle temperature, layer thickness, print speed, and infill % on surface roughness. They determined that layer thickness was the most influential factor. The researchers found that reducing the thickness of the bottom layer and increasing the temperature of the nozzle resulted in a decrease in surface roughness, which supports the results of Al Afghani et al. [18]. Higher print speeds resulted in an increased surface roughness, but the infill percentage did not have a significant effect which is consistent with Reddy et al. results [19].

The literature findings highlight the influence of several process parameters on surface roughness, such as layer thickness, build orientation, infill percentage, raster width, raster angle, and extrusion temperature. Out of these factors, build orientation had a diverse impact on surface roughness. However, the impact of build orientation in two axes including arbitrary angles and bi-directional raster angles with variable values across layers, has not been well investigated. These parameters were not thoroughly examined together to evaluate their main effects and interaction effects. This highlights the need to identify the key parameters that should be included in an expanded matrix to thoroughly investigate their main effects, interactions, and quadratic effects. The objective of this work is to examine the impact of crucial FDM process parameters on the surface roughness of PLA material.

2. Methodology

2.1.Parameters Selection.

Table 1 shows a list of process parameters and their respective value range, which was selected based on the existing literature and practical limits. The build orientation was defined in the current study as the orientation around the X-axis (O_X) and the orientation around the Y-axis (O_Y), allowing the analysis of the combined impacts of building orientation in various directions. Aiming at more thorough investigation of the raster angle, this study investgates the initial layer angle relative to the Y-axes (θ) and the angle between two consecutive layers (Δ), as described in Figure 2.

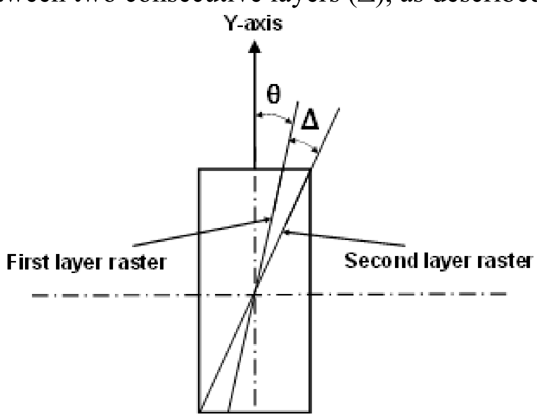

Figure 2 illustration of θ and Δ .

Table 1. parameters and their levels of study.

Factor	Units	Low	High
Layer thickness (mm)	mm	0.05	0.2
Infill percentage	%	20	80
Orientation around X- axis (O_X)	(°)	0	75
Orientation around Y-axis (O_Y)	(°)	0	75
Initial layer angle (θ)	(°)	5	40
Raster width	mm	0.3	0.45
Extrusion temperature	(°C)	195	225
Angle between successive layers (Δ)	(°)	5	40

2.2.Design of experiment.

Design of Experiments (DoE) is an approach used to determine the relationship between process parameters and resulting outcomes. DoE involves various experimental designs, including Taguchi experimental plans, central composite design (CCD), full factorial and fractional factorial experiments [20]. A full factorial experiment considers all possible combinations of factors and their levels, providing comprehensive interaction data but often requiring a large number of experiments.

On the other hand, a fractional factorial experiment reduces the number of trials by considering only a subset of possible combinations, making it more feasible while still offering useful insights into the main effects of factors [21]. In this study, A Resolution IV (2^{8-4}) fractional factorial experiment was used to identify the main effects of the eight factors being studied at two levels. The considered parameters are layer thickness, infill percentage, raster width, extrusion temperature, raster angle θ and angle between successive layers Δ θ, and build orientation in two plans represented by angles O_X and O_Y. The screening experiment related to this study was conducted by the authors in a previous study [22]; Figure 3 presents the results of these screening experiments.

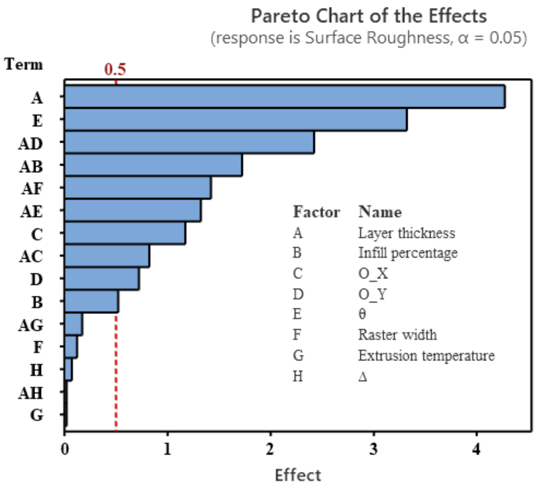

Figure 3. Results for surface roughness screening experiment [22]

Significant parameters were identified based on the results of the screening experiments. These identified significant parameters were included in the expanded experimental matrix in this work based on CCD to investigate the main effects, interactions, and quadratic effects of the significant parameters. CCD is a response surface methodology (RSM) that fits a quadratic equation to the experimental data, allowing for the modelling of non-linear relationships between parameters and the response[23].

This comprehensive approach seeks to offer a thorough understanding of the interactions and the impact of significant parameters on the surface roughness of FDM-printed PLA parts. A half-fractional CCD experiment was performed in this study using the Minitab® software. The design matrix developed consists of 46 runs, with five levels for each parameter. The parameters and their respective levels are listed in Table 2, while Table 3 shows the CCD experimental matrix.

Table 2. CCD parameters and levels of study

Factor	Name	Units	Low	High	Center point	-α	+α
A	Layer thickness	mm	0.1	0.2	0.15	0.05	0.25
B	Infill percentage	%	35	65	50	20	80
C	O_X	(°)	20	60	40	0	80
D	O_Y	(°)	20	60	40	0	80
E	θ	(°)	20	60	40	0	80

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Table 3. Surface roughness CCD Experimental Matrix and Results

Standard	Run	Layer Thickness (mm)	Infill percentage (%)	O_X (°)	O_Y (°)	θ (°)	Surface roughness (μm)
1	23	0.1	35	20	20	60	**14.8**
2	28	0.1	35	20	20	60	**15.8**
3	8	0.2	35	20	20	20	**30.32**
4	38	0.2	35	20	20	20	**29.56**
5	39	0.1	65	20	20	20	**15.68**
6	41	0.1	65	20	20	20	**14.56**
7	10	0.2	65	20	20	60	**30.96**
8	15	0.2	65	20	20	60	**30.16**
9	44	0.1	35	60	20	20	**11.08**
10	46	0.1	35	60	20	20	**11.16**
11	20	0.2	35	60	20	60	**18.44**
12	30	0.2	35	60	20	60	**18.6**
13	18	0.1	65	60	20	60	**11.36**
14	6	0.1	65	60	20	60	**12.24**
15	26	0.2	65	60	20	20	**18.36**
16	29	0.2	65	60	20	20	**18.28**
17	27	0.1	35	20	60	20	**10.36**
18	45	0.1	35	20	60	20	**11.28**
19	11	0.2	35	20	60	60	**12.16**
20	12	0.2	35	20	60	60	**12.88**
21	42	0.1	65	20	60	60	**11.04**
22	16	0.1	65	20	60	60	**10.84**
23	22	0.2	65	20	60	20	**12.12**
24	24	0.2	65	20	60	20	**13.96**
25	32	0.1	35	60	60	60	**11.76**
26	7	0.1	35	60	60	60	**11.80**
27	33	0.2	35	60	60	20	**18.12**
28	37	0.2	35	60	60	20	**17.76**
29	31	0.1	65	60	60	20	**11.36**
30	5	0.1	65	60	60	20	**12.12**
31	35	0.2	65	60	60	60	**18.24**
32	36	0.2	65	60	60	60	**16.84**
33	43	0.05	50	40	40	40	**11.2**
34	17	0.25	50	40	40	40	**24.16**
35	13	0.15	20	40	40	40	**17.88**
36	25	0.15	80	40	40	40	**18.00**
37	19	0.15	50	0	40	40	**17.91**
38	2	0.15	50	80	40	40	**10.52**
39	9	0.15	50	40	0	40	**20.41**
40	14	0.15	50	40	80	40	**7.92**
41	1	0.15	50	40	40	0	**18.00**
42	34	0.15	50	40	40	80	**18.12**
43	4	0.15	50	40	40	40	**18.92**
44	3	0.15	50	40	40	40	**17.56**
45	40	0.15	50	40	40	40	**17.64**
46	21	0.15	50	40	40	40	**18.8**

2.3.Experimental work.

Rectangular test specimens were used in this study for surface roughness measurements with the dimensions depicted in Figure 4. All specimens were fabricated using an Ultimaker-3 printer with a 0.4 nozzle diameter. They were digitally modelled and saved in STL format using Ultimaker Cura 4.12.1 slicer software, allowing for exact control over the printing settings. The main structure and the support structure were printed using the same nozzle and material. PLA material with a filament diameter of 2.85 mm was used for printing. The selection of PLA was chosen for its excellent mechanical strength, stiffness, and thermal stability, making it suitable for both functional prototypes and final parts [24]. Surface roughness was conducted using a contact-type profilometer with specific parameters. The cutoff length was set at 0.8 mm, representing the distance over which surface roughness is measured to filter out waviness to focus only on the smaller-scale irregularities.

The evaluation length was chosen as 4 mm, which is the total distance over which the roughness measurements were averaged. The range was set to 100 µm, representing the maximum vertical height the profilometer can measure. These parameters ensure an accurate quantification of the surface roughness values of the printed specimens. A Surtronic S25 stylus profilometer, shown in Figure 5, was used to measure the surface roughness of the topside. The profilometer probe moved in a perpendicular direction to the raster angle, to ensure accurate measurement of surface irregularities. The Ra value, representing the arithmetic average roughness, was the primary metric used to quantify surface roughness. The mean value of five measurements of surface roughness was calculated for each test based on the average of peaks (Ra).

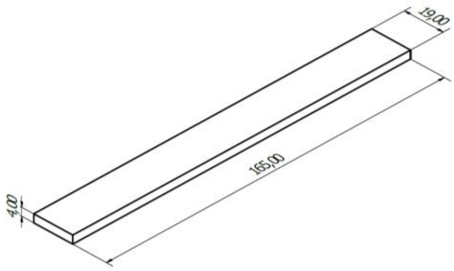

Figure 4. Rectangular Specimen dimensions

Figure 5. Surtronic S25 stylus profilometer

3. Results of the CCD model.

The results of the expanded CCD are shown in Table 3. These data were used to create a coded equation (1), that represents a mathematical relationship between the outcome and the included parameters as follows:

$$Surface\ roughness = 18.01 + 3.64(A) + 0.062\ (B) - 1.34\ (C) - 2.84\ (D) + 0.052\ (E) - 0.5\ (AC) - 1.7\ (AD) + 2.68\ (CD) - 0.9606\ (C^2) - 0.9731\ (D^2) \quad \textbf{(1)}$$

Where,

A……	Layer thickness	AC….	Layer thickness and O_X interaction
B……	Infill percentage	AD….	Layer thickness and O_Y interaction
C……	O_X	CD….	O_X and O_Y interaction
D……	O_Y		
E……	θ		

An Analysis of Variance (ANOVA) test was conducted to assess the data. Table 4 demonstrates the significance of the main effects and interactions. It reveals the significance of the model and the insignificance of the lack of fit, indicating that the model fits the data well. The model significance is further reinforced by the predicted vs observed plot shown in Figure 6. The fitting accuracy of the model is supported by the fit statistic parameters listed in Table 5. The normal probability plot in Figure 7 confirms the ANOVA test assumption that residuals are normally distributed. In conclusion, the model's adequacy was verified as it fits the experimental results perfectly. It was found that build orientation around the X and Y axes, as well as layer thickness, are significant parameters. In contrast, infill percentage and raster angle were found to be insignificant. The following section will discuss each significant parameter and interaction in detail.

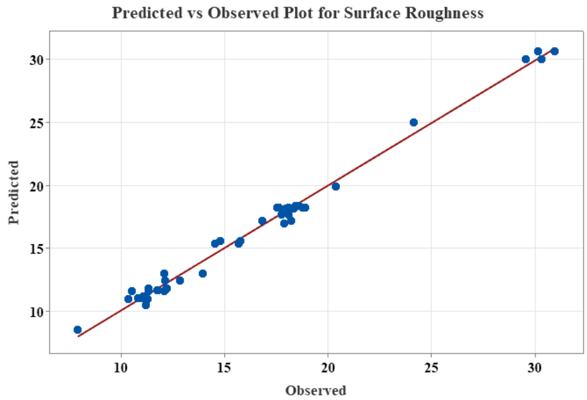

Figure 6. Predicted vs Actual plot for Surface roughness

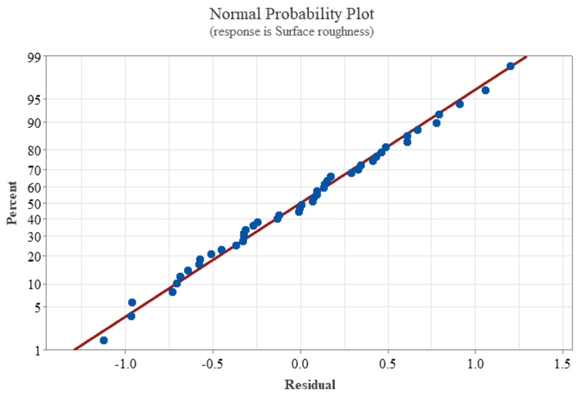

Figure 7. Normal Probability plot

Table 4. ANOVA table for Surface roughness

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	1384.93	11	125.90	307.49	< 0.0001	significant
A-Layer Thickness	528.82	1	528.82	1291.51	< 0.0001	
B-Infill percentage	0.1538	1	0.1538	0.3755	0.5441	
C-O_X	72.20	1	72.20	176.33	< 0.0001	
D-O_Y	323.19	1	323.19	789.32	< 0.0001	
E- θ	0.1082	1	0.1082	0.2642	0.6106	
AC	8.00	1	8.00	19.54	< 0.0001	
AD	99.69	1	99.69	243.46	< 0.0001	
CD	229.41	1	229.41	560.27	< 0.0001	
C^2	26.72	1	26.72	65.25	< 0.0001	
D^2	27.42	1	27.42	66.95	< 0.0001	
Residual	13.92	34	0.4095			
Lack of Fit	6.45	15	0.4301	1.09	0.0796	not significant
Pure Error	7.47	19	0.3932			
Total	1398.85	45				

Table 5. Fit statistic of the model

R^2	0.9900
Adjusted R^2	0.9868
Predicted R^2	0.9794

4. Discussion

In Figure 8, the impacts of the different processing factors examined in this study were illustrated. Table 4 indicates that the infill percentage and raster angle have no significant impact on the enlarged matrix. This is consistent with previous research that confirmed the insignificant effect of infill percentage and raster angle compared to layer thickness and build orientation [19,25]. Figure 8a shows the relationship between layer thickness and surface roughness. Increasing layer thickness causes an increase in surface roughness. These results align with previous studies, confirming the significance of layer thickness on surface roughness [11,12,15,26,27]. The key difference of this study is the inclusion of layer thickness as one of eight process parameters evaluated through a comprehensive screening and expanded matrix approach. Unlike previous studies [11,12,15,26,27], which primarily examine layer thickness with two or three parameters, this work investigates both main and interaction effects.
This deeper analysis addresses a gap in the literature by providing a more thorough understanding of the combined influence of multiple process parameters on surface roughness.
Increased layer thicknesses led to a more noticeable staircase effect, resulting in a rougher surface roughness. The stair-step effect arises when thicker layers create more noticeable steps between each layer, which in turn reduces the accuracy of the printed geometry and increases surface roughness. In addition, thicker layers contribute to the promotion of surface waviness, which is likely caused by the greater shrinking effect found in higher layers. This reduction in size leads to a more noticeable waviness. Thinner layers, on the other hand, improve the resolution and surface quality of the printed part by minimizing these steps and waviness [25,26]. The effect of layer thickness on surface roughness can be analogized to the influence of the nose radius in traditional machining when turning workpieces. In both cases, larger layer thickness in FDM and a larger nose radius in machining result in more pronounced surface irregularities. This is because, just as the nose radius determines the contour and smoothness of the machined surface, the layer thickness in FDM defines the height of the steps between layers. Thicker layers create larger step heights, increasing surface roughness, similar to the way a larger nose radius can affect the finish of a machined part.

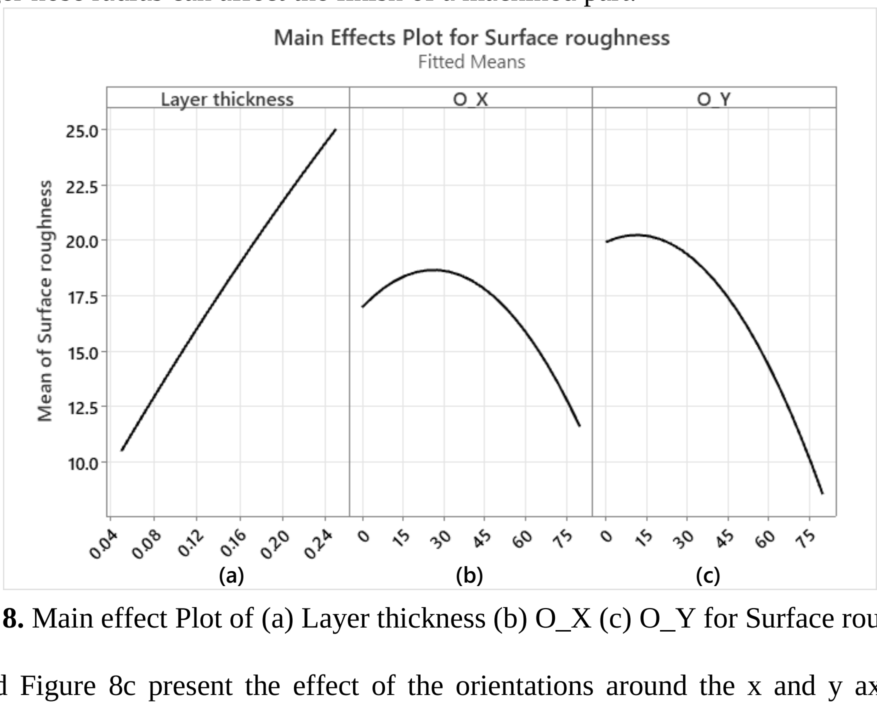

Figure 8. Main effect Plot of (a) Layer thickness (b) O_X (c) O_Y for Surface roughness.

Figure 8b and Figure 8c present the effect of the orientations around the x and y axes on surface roughness respectively. It was observed that increasing the orientation angle causes a decrease in surface roughness. Specifically, the flat position (0° for both orientations) yielded the worst surface finish compared to the upright position (90 degrees around the X-axis) and the on-edge position (90 degrees around the Y-axis). These findings are consistent with previous studies that also reported that an increased orientation angle leads to improved surface quality [12,15,16]. However, they contradict the results of Buj et al. [14]. The effect of build orientation on surface roughness showed a non-linear relationship, as evidenced by the significant quadratic terms for both orientation factors. This non-linearity resulted in a slight increase in surface roughness between 0 and 20 degrees. Such an outcome regarding the decrease in roughness with increasing both orientations can be attributed to the different functions of raster width and layer thickness controlling surface roughness.

Additionally, Table 4 highlights the significant interactions affecting surface roughness. The significant interactions were analyzed using interaction plots and response surface plots, as shown in Figure 9, Figure 10, and Figure 11.

Figure 9 represents the interaction between layer thickness and O_X (AC). At both minimum and maximum values of O_X, an increase in layer thickness leads to an increase in surface roughness. However, this increase is steeper at the lowest O_X value. Similarly, Figure 10 illustrates the same trend for the interaction between layer thickness and O_Y (AD). At both the lowest and highest values of O_Y, increasing layer thickness results in higher surface roughness, with the same steeper at the lowest O_Y value.

The stair-stepping effect serves as the controlling phenomenon that illustrates the interaction effects between build orientation and layer thickness. This effect becomes more pronounced with a decrease in the number of layers at higher layer thicknesses. Additionally, as build orientation decreases, the stair-stepping effect becomes more evident due to the increased distance between successive steps created by the orientation angle. The stair-stepping effect is noticeable at any angle above 0 degrees, where layer thickness becomes the dominant factor influencing roughness. This analysis does not apply to the flat position, as previously mentioned raster width is the dominant parameter in controlling roughness in that orientation, and the stair-stepping effect does not occur. The combined negative effect of decreasing build orientation along with higher layer thickness results in increased surface roughness.

In contrast, Figure 11 depicts a different trend for the interaction between O_Y and O_X (CD). At lower values of O_Y, an increase in O_X led to a reduction in surface roughness. Conversely, at higher values of O_Y, increasing O_X results in an increase in surface roughness. In general, the interaction analysis further confirms that the optimal orientation for achieving the lowest roughness is at 90 degrees for both orientation angles.

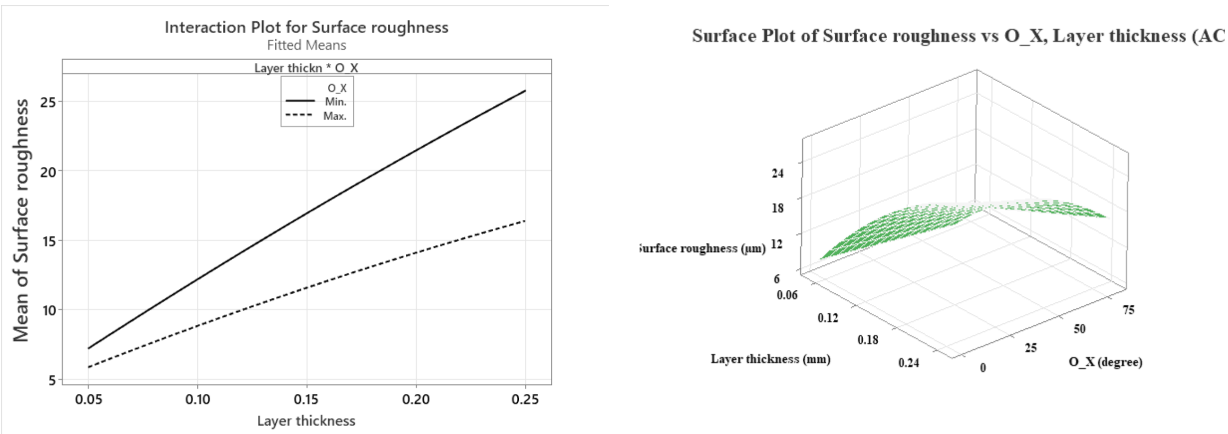

Figure 9. interaction and surface plot for Surface roughness vs Layer thickness and O_X (AC)

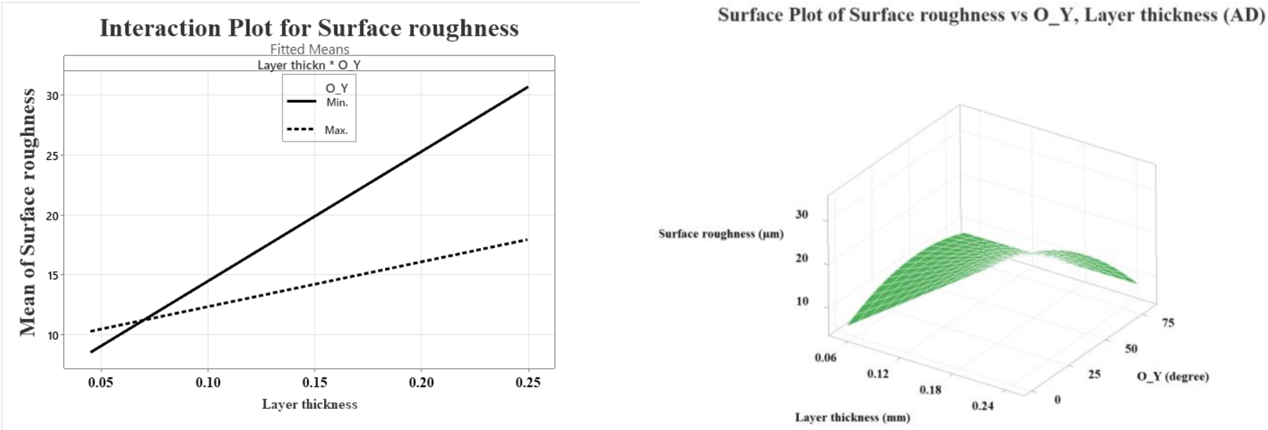

Figure 10 interaction and surface plot for Surface roughness vs Layer thickness and O_Y (AD)

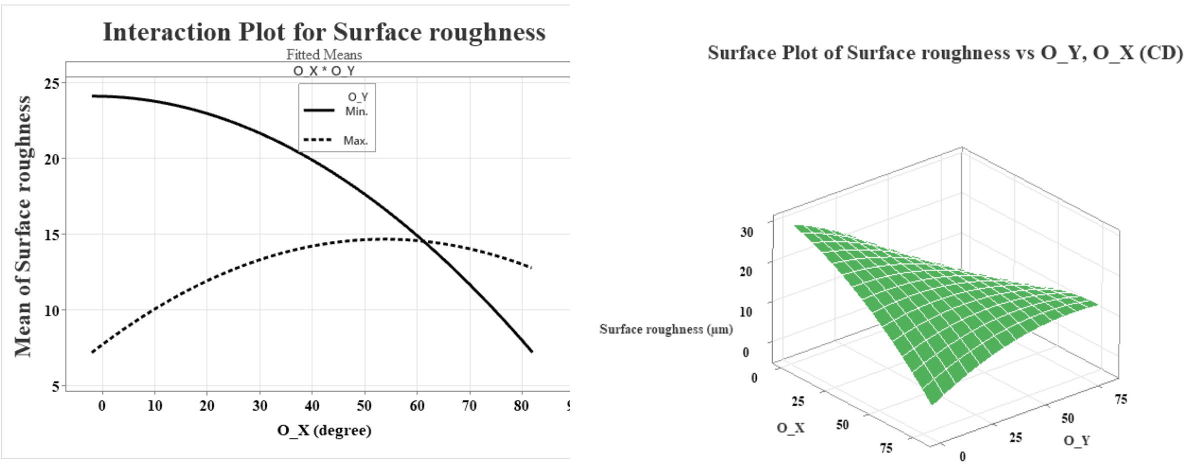

Figure 11. interaction and surface plot for Surface roughness vs O_X and O_Y (CD)

5. Conclusion.

In this study, eight FDM process parameters were thoroughly investigated using CCD to assess their main, interaction and quadratic effect. ANOVA test was conducted and confirmed the model's adequacy. The high R-squared values indicated a strong fit. The findings indicated a direct relationship between layer thickness and surface roughness. The interaction between infill percentage and raster angle had a significant impact on surface roughness, even though their main effect was insignificant. In addition, an improvement in surface roughness was observed with an increase in orientation around the X and Y axes, particularly at higher angles which resulted in the best roughness values. Notable interactions were observed between layer thickness and orientation around the Y axis (O_Y), as well as between orientations around the X and Y axes. The findings presented in this study provide valuable insights into the impact of various process parameters on surface quality. This study establishes a framework for future studies to further optimize these parameters.

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