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ANALYSIS AND PREDICTION OF WORKING RANGE OF PROCESS PARAMETERS FOR SURFACE ROUGHNESS OF 3D PRINTED PARTS WITH FUSED DEPOSITION MODELLING

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ABSTRACT

A current manufacturing scenario focuses on processes which can manufacture products at the highest quality with minimum wastage of material. Additive manufacturing is one such technology which can fulfil the demands of today's manufacturing organisation. Fused Deposition Modelling is a 3D printing process from the additive manufacturing family to build polymer components accurately with almost negligible wastage of material. In the current investigation, analysis and prediction of the operating range of process parameters for surface roughness of 3D printed parts are presented. During the investigation, orientation is an essential aspect of the surface of fused deposition modelling printed parts. From contour plots, it is concluded that orientations 0º to 15º and 85º to 90º with a layer thickness range of 0.12 mm to 0.16 mm and Infill density within 80% to 90% are found to be suitable working range for better surface roughness below 6 µm.

Keywords: *Additive Manufacturing; Fused Deposition Modelling; Surface Roughness; Build Orientation; Layer Thickness; Infill Density; ANOVA.*

1. Introduction

Fabricating components from a CAD model by stacking and merging layers to achieve the desired physical model is referred to as additive manufacturing [1]. Many AM processes can manufacture any integrated shape from a wide range of materials like polymers, resins and metal powder. Fused Deposition modelling (FDM), introduced by Stratasys in 1991, is one of the most widely used additive manufacturing processes for polymers [2-3]. In FDM, raw material in wire form is fused into a thermostat and deposited through a nozzle which follows the path defined by a computer program to create a 3-Dimensional object. After one layer is deposed, the bed lowers, or the nozzle kit raises to fabricate the adjacent layer [4] successfully. The performance of Fused Deposition Modelling depends on process parameters like layer thickness, raster width, air gap, build orientation, infill density, printing speed etc. The performance is measured in surface roughness, build time, material consumed and sometimes in the form of strength of the material.

To assess the performance of FDM and the quality of manufactured parts with FDM, apart from size and shape, surface roughness is the most important aspect. Altan et al. [5] used an L16 array with variation in layer thickness from 0.1 mm to 0.4 mm to fabricate PLA samples using FDM. They found variation from 9.102µm to 10.275 µm in surface roughness for above layer thickness. According to them, layer thickness and deposition head velocity are the most influencing parameters in surface roughness. According to Gautham et al. [6], in the surface angle range40-90°, the surface roughness rate (Ra) variation is lesser than in the 0-40° surface angle range. With layer thickness of 0.2 mm, printing speed of 60 mm/s, and extrusion temperature of 240 °C lowest means of surface roughness can be found [7]. Akande et al. [8] found surface roughness ranges from 2.46 to 22.48 µm, with a layer height varying from 0.25 to 0.5mm. Vasudevarao et al. [9] set different parameters to determine surface roughness and proved that Layer Thickness and Part Orientation are the factors which have the highest impact on surface roughness. A layer thickness of 0.007 inches and orientation of 70° have the best surface finish. Model Temperature, air Gap and Road Width did not influence the part's surface finish. Pandey et al. [10] considered side angles of 10°, 15°, 30° and 45° with a layer thickness of 0.254 mm for the pyramid specimen for assessment of the surface roughness. They have derived a model for surface roughness based on layer thickness and build orientation. A smaller layer thickness indicates a smaller layer height during printing; therefore, at a smaller layer thickness better surface can be found [11]. Byun and

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Lee [12] studied several Rapid Prototyping techniques, and found the best build-up direction when a part is created with variable layer thickness.

The procedure considers the average weighted surface roughness (AWSR) caused by the staircase effect and the build time and part cost using variable layer thickness. According to Khan and Mishra, the air gap has the highest impact on the surface of ABS printed parts [13]. Surface roughness can be improved by lowering the layer thickness [14]. The surface roughness of FDM printed specimens is investigated by Galantucci et al. [15] and found that slice height and raster width are particularly essential factors for surface roughness considerations. In contrast, the tip diameter is less important for surfaces that run parallel or perpendicular to the build direction. The optimum surface roughness can be found by combining higher infill density and lower layer height [16]. According to Mendricky and Fris [17], layer height, top layer shape, and fill print speed are the most influential parameters on the surface roughness of the top layer.

In contrast, layer height and the part's orientation on the base influence the side wall's surface roughness. Much research has been done on the surface roughness of FDM-printed Parts. Many scopes are still there to make a detailed analysis of surface roughness to find the working range of process parameters for FDM. This paper presents a detailed analysis of surface roughness based on Layer thickness, Infill density and Build orientation. A working range of these parameters for a better surface finish is also suggested in this analysis.

2. Experimental Setup

The details of the experimental setup are given in Table 1, along with the specifications. Three process parameters, each having three levels, are selected to assess the effects of parameters on the roughness of FDM printed parts. These process parameters and their levels are given in Table 2.

One of FDM's most important process parameters is orientation while considering surface roughness. Fig. 1 shows the sliced components at various build orientations.

Table 1 Details of Experimental Work

Item	Details
3D Printing technology	Fused Deposition Modelling
3D Printer	Flashforge Finder 3D printer (140 mm^3).
Filament Diameter	1.75 mm
Nozzle Diameter	0.4 mm
Slicing Software	Flashprint
File Type	STL
Nozzle Temperature	220^o C
Infill Pattern	Line
Shell Thickness	0.80 mm
Material	Polylactic Acid (PLA)
Specimen Specifications	Rectangular Block (40L*30W*10H mm).
Roughness Measurement	Mitutoyo SJ-210

Table 2 Details of Experimental Work

Process Parameters	L1	L2	L3
Layer Thickness (mm)	0.12	0.14	0.16
Infill Density (%)	80	85	90
Build orientation (^{o})	0	45	90

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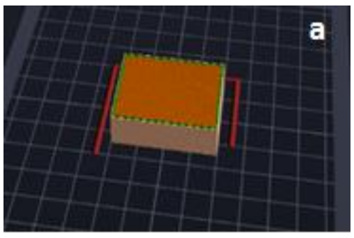
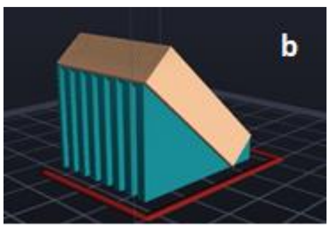
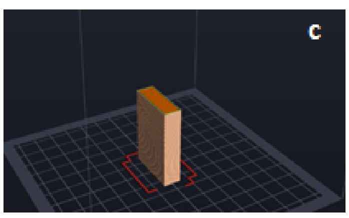


(a) 0º Orientation



(b) 45º Orientation



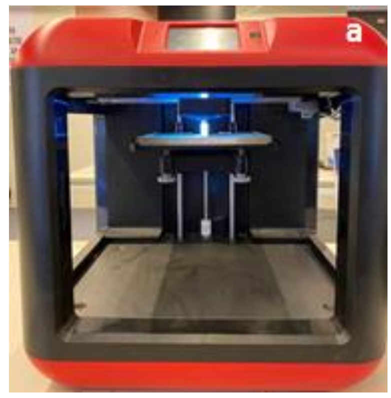
(c) 90º orientation

Fig. 1 Sliced Components

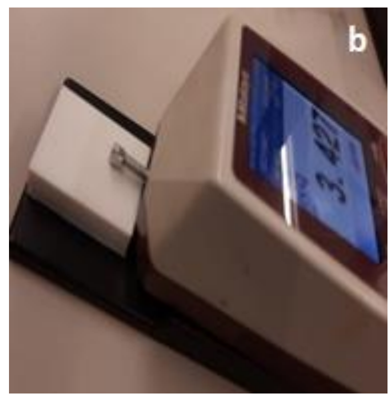
Taguchi L_9 array is created using three factors at three levels for selected process parameters in the Minitab software. Table 3 shows the Taguchi L_9 array.

Table 3 Taguchi's L_9 Array for Selected Parameters

Layer Thickness	Infill Density	Orientation	Ra
0.12	80	0	2.94
0.12	85	45	8.636
0.12	90	90	5.33
0.14	80	45	9.734
0.14	85	90	3.428
0.14	90	0	3.076
0.16	80	90	3.785
0.16	85	0	3.018
0.16	90	45	10.533



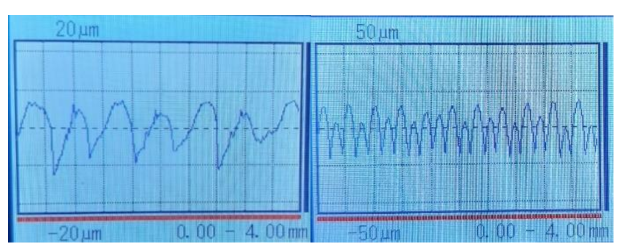
(a) 3D printing set up



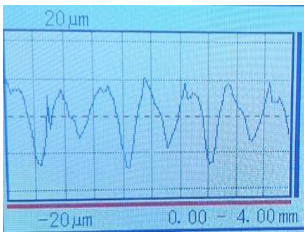
(b) Testing of Fabricated Parts

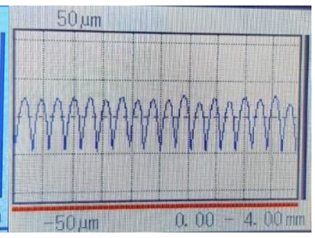
Fig. 2 Set up of Printer and Testing of Specimen

After printing nine components (as shown in Fig.2.a), surface roughness is measured using Mitutoyo SJ-210 portable roughness tester. Measurements are carried out at three different points for every component, and the mean of those values is considered the final Ra value for analysis. The surface roughness set is shown in Fig. 2.b. Fig.3 surface roughness peak and valley trends for all nine specimens.

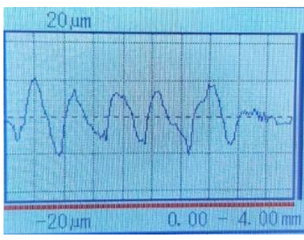


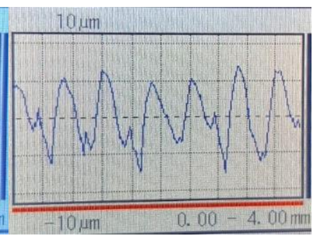
Experiment 1 **Experiment 2**



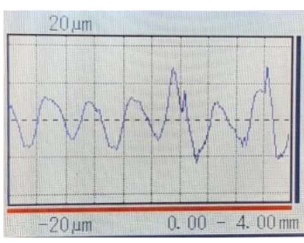


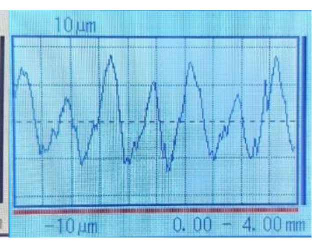
Experiment 3 **Experiment 4**



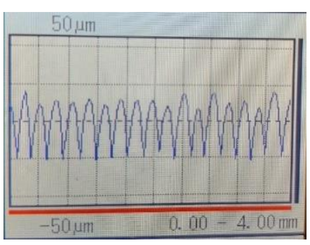


Experiment 5 **Experiment 6**





Experiment 7 **Experiment 8**



Experiment 9

Fig. 3 Roughness Peak and Valley Trend

3. Results and Discussion

ANOVA and mean effect plots are used to see the effect of process parameters in this investigation on surface roughness. ANOVA is shown in Table 4, and mean effect plots are shown in Fig. 3. p-value is used at a 95% confidence level (0.05) to judge the significance of process parameters on Surface roughness. It is clear from Table 4 that orientation significantly affects surface roughness as the p-value for orientation is 0.015, which is less than 0.05. The other two parameters do not significantly affect surface roughness as the p-values for layer thickness and infill density are 0.826 and 0.296, respectively, which are larger than 0.05. From table 4, the surface roughness values, R^2 is 98.59%, and adjusted R^2 equals 94.37% R2 (pred) is 71.50%, which indicates that the model explains 71.50% of the variation in surface roughness with the selected working range.

Table 4 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	p-Value
Layer Thickness	2	0.236	0.118	0.21	0.826
Infill Density	2	2.673	1.337	2.38	0.296
Orientation	2	75.686	37.843	67.46	0.015
Error	2	1.122	0.561		
Total	8	79.717			

To get clarity of the trend of surface roughness with respect to process parameters under investigation, mean effect plots are prepared. Fig. 4 shows the mean effect plot of the Ra value. The mean of surface roughness is 5.64 µm at 0.12 mm layer thickness, 5.41 µm at 0.14 mm layer thickness and 5.808 µm at 0.16 mm layer thickness. Therefore, the minimum mean surface roughness is found at 0.14 mm layer thickness. The percentage increase in surface roughness at 0.12 mm layer thickness is 4.12% as compared to 0.14 mm layer thickness. Similarly, the percentage increase in surface roughness at 0.16 mm layer thickness is 7.32% as compared to 0.14 mm layer thickness. This indicates that smaller layer thickness results in a better surface finish because layer thickness actually in printing is layer height. So smaller layer height produces a nearly continuous surface.

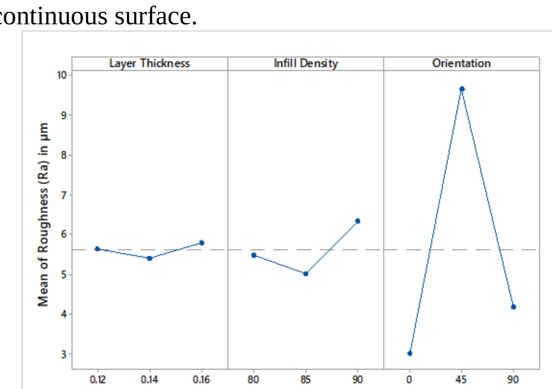


Fig. 4 Mean Effect Plot for Ra Value

The mean of surface roughness at 80% infill density is 5.486 µm, at 85% infill density is 5.027 and at 90% infill density is 6.342 µm. Therefore, the minimum mean surface roughness is found at 85% infill density. The percentage increase in surface roughness at 80% infill density is 9.13% as compared to 85% infill density. Similarly, the percentage increase in surface roughness at 90% infill density is 26.16% as compared to 85% infill density.

From the mean effect plot, it can be observed that the mean of surface roughness value Ra at 0° orientation is 3.011 µm, at 45°orientation is 9.664 µm and at 90° orientation is 4.181 µm. Therefore, the minimum mean surface roughness is found at 0°orientation. The percentage increase in surface roughness at 45° orientation is 220.13% as compared to 0° orientation. Similarly, the percentage increase in surface roughness at 90° orientation is 38.85% as compared to 0° orientation. It indicates that lesser inclination results in better surface finish because the nozzle travels on a plane normal to the component's surface. From Fig.3 It is observed from trend that the range of Ra with respect to peak and valley for 0° and 90°are contained within -20 to +20 µm; it is clear that the actual value of peak and valley are below 5µm. For 45° orientation, the range is contained within -50 to +50 µm, and peak-valley values are up to 10 µm.

Table 5 Response Table for Means (Ra)

Level	Layer Thickness	Infill Density	Orientation
1	5.635	5.486	3.011
2	5.412	5.027	9.664
3	5.808	6.342	4.181
Delta	0.396	1.315	6.653
Rank	3	2	1

From the analysis of the response in Table 5, it can be seen that the delta value (the difference between the maximum and minimum mean surface roughness) for layer thickness delta value is 0.396, for infill density delta value is 1.315 and for orientation is 6.653. Based on this, process parameters' significance and ranking are given below. As the highest delta value corresponds to the orientation, it has 1st rank. Infill density has 2nd most significant delta value and therefore ranks at 2nd position. Layer thickness is at 3rd rank with the lowest delta value. It indicates that orientation is the most influencing parameter as surface roughness is considered.

A response table for the mean is prepared better to judge preferences of the influence of process parameters. So altogether, for the current analysis, it is found that the orientation with which the components are printed matters a lot in fused deposition modelling as per as surface roughness is concerned.

To decide the operating range of orientation, layer thickness and infill density for better surface roughness results, surface contour plots are drawn. Hence orientation is focused as it has the highest significance, so contour plots are drawn for the combination of orientation-layer thickness and orientation-infill density. The contour plots are shown in fig 5 and 6. In these contour plots, the working ranges of orientation, layer thickness and infill density for better surface finish are decided based on shades of colour on the plot. In this plot, the shades are darkest green, darker green, basic green, lighter green and lightest green. The feasible working range is decided based on surface roughness values less than 4 (lightest), from 4 to 6 (lighter). All values of surface roughness above this are not suitable. The ranges are 6 to 8 (basic green), 8 to 10 (darker green) and above 10 (darkest green).

From fig. 5, the orientation of 0° with layer thickness from 0.12 mm to 0.16 mm and orientation of 90° with a layer thickness of 0.13 mm to 0.16 mm is suitable for surface roughness as it shows the lightest green color, which is below 4 µm. Orientation up to 15° is also suitable with a layer thickness of 0.12 mm to 0.16 mm as it has a lighter green shade in the range from 4 µm to 6 µm. Orientation of 85° with the combination of 0.12 mm to 0.16 mm layer thickness is suitable for surface roughness consideration as this also shows a lighter green shade with surface roughness range from 4 µm to 6 µm.

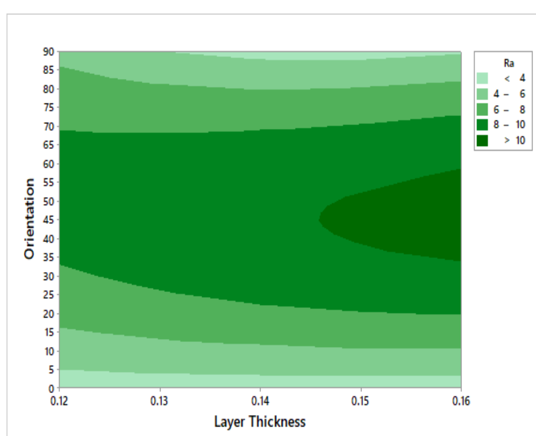


Fig. 5 Contour Plot for Orientation-Layer Thickness

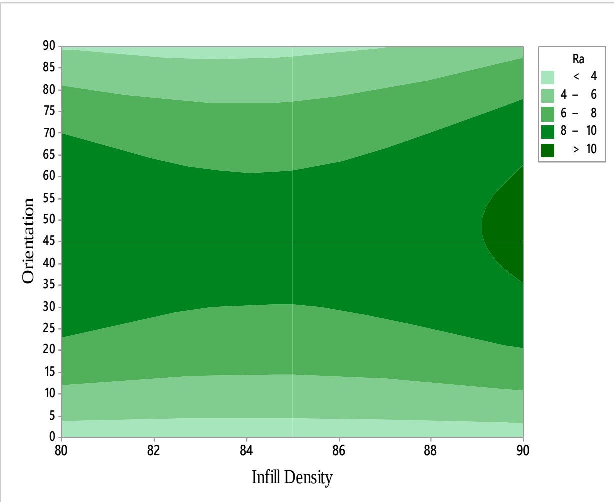


Fig. 6 Contour Plot for Orientation-Infill Density

From fig. 6, the orientation of 0° with Infill density of 80% to 90% and orientation of 90° with Infill density of 80% to 87% is suitable for surface roughness as it shows the lightest green colour which is below 4 µm. Orientation up to 10° is also suitable with an Infill Density of 80% to 90% as it has a lighter green shade in the range from 4 µm to 6 µm. Orientation of 80° with a combination of 80% to 90% Infill density is suitable for surface roughness as this also shows a lighter green shade with surface roughness from 4 µm to 6 µm.

Altogether, orientations 0º to 15º and 85º to 90º with layer thickness range of 0.12 mm to 0.16 mm and Infill density range from 80% to 90% are found to be a suitable working range for better surface roughness below 6 µm.

4. Conclusions

This work presents an analysis and prediction of the Working range of process parameters for surface roughness of 3D printed parts with Fused Deposition Modelling. Following are some of the critical conclusions of this work.

i. The build orientation is significant for surface roughness considerations as it significantly affects surface roughness for the range used in this investigation.
ii. The significance of build orientation on surface roughness is confirmed from ANOVA as the p value for build orientation is 0.015, which is less than 0.05.
iii. Surface roughness values (Ra) for 0° and 90° range from 2 to 5 µm. In comparison, Ra values for 45° are between 8 to 10 µm.
iv. From contour plots, it can be concluded that orientations 0º to 15º and 85º to 90º with layer thickness range of 0.12 mm to 0.16 mm and Infill density range from 80% to 90% are a suitable working range for better surface roughness below 6 µm.

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