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Process optimization of additively manufactured PLA specimens on surface quality using the Taguchi method

Siddhant R. Gade, Shashikant T. Vagge[1]

Department of Metallurgy and M.S.,College of Engineering, Pune, 411005, India

Abstract

Additive manufacturing (AM) is the procedure in which parts are fabricated in a layer-by-layer manner, exactly the opposite of conventional manufacturing, in which material is removed. Nowadays, in this emerging generation, additive manufacturing is usually preferable over traditional manufacturing methods owing to its better accuracy, less time for manufacturing, lower cost, and good quality of products. The present paper discusses the fabrication of additively manufactured PLA specimens. Optimization of process variables was done by using the Taguchi method in order to get sound three-dimensional parts. The fused deposition modeling method was employed for the experimental study. An orthogonal array (L27) was created by using three levels and three parameters for the Design of Experiments (DoE). The research community has given little attention to the surface quality attained in the AM process. As a result, the purpose of this study is to fill that research gap. The main objective is to identify essential process parameters and their significance in FDM procedures that might help to reduce surface roughness. Three printing factors (layer thickness, printing speed, and filling percentage) with three levels were investigated using the Taguchi approach. Results showed that the surface roughness values (Ra) fluctuated between 2.07 microns (lowest) to 3.78 microns (highest) for 27 samples. The layer thickness was the most significant process variable as compared to other factors. Lower levels of layer thickness and printing speed were responsible for getting a good surface quality of the additively manufactured component.

Keywords: Additive manufacturing; Surface Roughness; Taguchi method; Fused Deposition Modeling

1. Introduction

Nowadays, manufacturing lays a strong focus on speed, precision, adaptability, and waste minimization. As a result, there has been a surge in interest in the field of Additive Manufacturing (AM). While traditional manufacturing processes such as machining are based on removing material from bulk form, the basis of 3D printing is to construct an item layer by layer by adding up material [1]. Additive Manufacturing is on the cutting edge of research for creating a wide range of items and has been dubbed the "third industrial revolution" [2]. In suitable applications, additive manufacturing offers advantages such as improved performance, complex geometry production, and simplified fabrication. Surface roughness is an important characteristic that is targeted to get the minimum value which in turn results in sound surface quality. Surface roughness enhances the aesthetic view of the product.

1.1. Fused deposition modeling (FDM)

FDM is one of the simplest AM techniques in which the spooled filament is heated to a semi-liquid phase at the nozzle prior to its extrusion onto the platform or above previously printed layers [3]. This process relies on

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[1] Corresponding author.

the polymer’s thermoplasticity, in which filaments fuse together during the printing process and then harden at ambient temperature [4]. The key advantages of this technique are that no post-processing is necessary, there are no resins to cure, the equipment and materials are less costly, and the procedure is more cost-effective [5]. FDM principle is primarily based on the material’s extrusion property of polymers shown in Fig 1. [6].

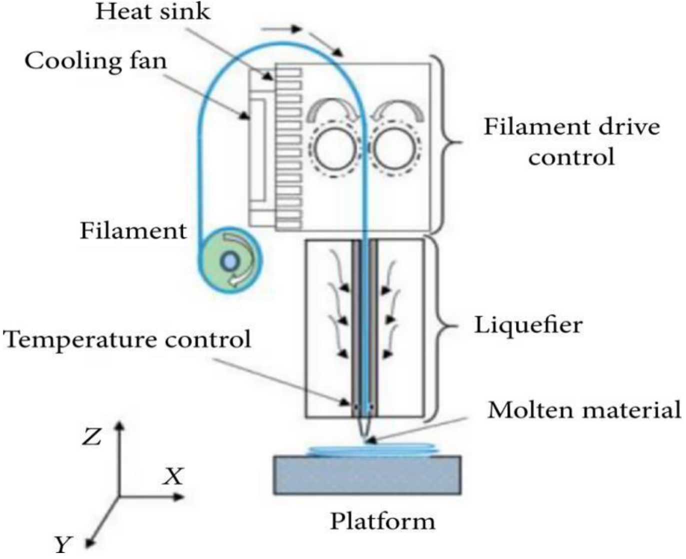

Fig. 1. FDM principle [6]

Process variables play a vital role in research, so they should be correctly optimized in order to get sufficient part quality. FDM has several process parameters that directly affect the properties of the manufactured product. Some process variable used in FDM are Layer Thickness [7-16], Raster Angle [7-12,16], Air Gap [7-12,16], Raster width [7,8,11,12,13,16], Build Orientation [7,8,9,12,14,16,17], Infill density [10,15], Infill pattern [14] and Printing Speed [9,13-15].

Due to the staircase effect and STL file resolution, one of the disadvantages of the FDM technique is high surface roughness [18]. The effect of process factors on surface roughness is dependent not only on the geometry of a component but also on how they are configured. Selecting the best combination of process settings helps enhance the surface quality of a part. Post-processing costs are often reduced when the surface quality is higher.

Vasudevarao et al. evaluated the effect of various process factors on surface roughness [19]. A Half factorial design was used to assess components manufactured by the FDM machine. The experiment findings revealed that low layer thickness and high build orientation lowered surface roughness, while other factors were less influential. Altan et al. investigated the input variable’s influence on surface roughness and tensile strength of PLA parts [20]. The experimental design used an orthogonal array of L16. PLA samples were created using an FDM method with layer thicknesses (0.1 mm to 0.4 mm). The surface roughness obtained ranged between 9.102 and 10.275 microns. The authors came to the conclusion that layer thickness and printing velocity are important determinants of surface roughness. According to Anitha et al., layer thickness was discovered to be the essential parameter for surface quality [21]. Surface quality was approximately equally affected by raster width and print speed. Thrimurthulu et al. also postulated a thin layer thickness for a good surface finish [22]. Campbell et al. studied surface roughness for several materials [23]. The scientists discovered that while utilizing a layer thickness of 0.253 mm for ABS material, the roughness values for FDM procedures were between 9 and 40 microns. Bakar et al. investigated a top surface has a better surface quality than a side surface [24]. They also suggested that for optimal surface quality, a lower layer thickness is preferred.

Akande et al. recently investigated the ideal process parameters for achieving high surface quality of cuboidshaped PLA specimens using a full factorial design [25]. The scientists used a layer thickness of 0.25 and 0.5 mm, adjusting the filling density and deposition speed, and discovered that the roughness values fell between 2.46 µm and 22.48 microns. Perez et al. fabricated a cylindrical-shaped specimen [26]. Their studies revealed that minimal layer height was preferred for effective surface finishing, while other factors such as extrusion temperature and print speed had little effect. Above mentioned researchers have worked on various process factors that affect the surface quality of the product. The Most common process factors were layer thickness and printing speed which were frequently used by the researchers and in our experimentation also.

2. Experimental work

In this study, optimization of process variables was done by using the Taguchi method in order to get sound three-dimensional parts. FDM technique was incorporated for the experimental study. An orthogonal array (L27) was created by using three levels and three parameters for the Design of Experiments (DoE), as shown in Tables 1 and 2. We have used L27 Full Factorial design rather than L16 orthogonal array as used by Altan et al. to get more clarity of results. Levels were decided considering the printer specifications, and based on some literature survey, Minitab 20 software was used to plot the graphs of Signal to Noise (S/N) ratios and interaction plots. The DoE process is shown in Fig. 2.

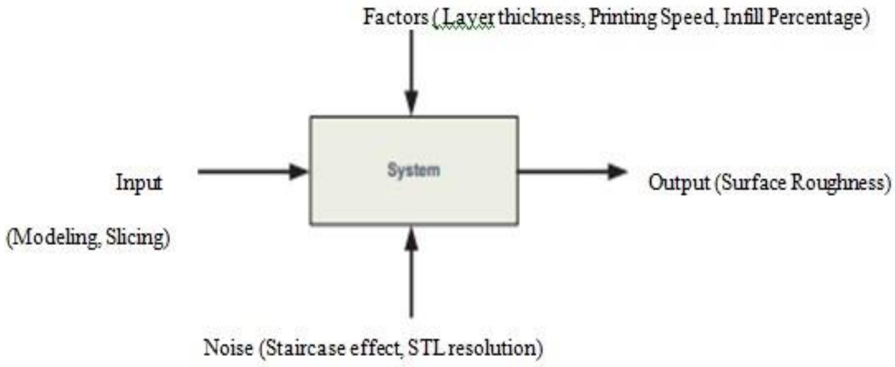

Fig. 2. Design of Experiment

Table 1. Factors and Levels used for Experimentation

Sr. no.	Process Factors	Level 1	Level 2	Level 3
1	Layer Thickness (mm)	0.14	0.17	0.20
2	Printing Speed (mm/sec)	20	30	40
3	Infill Percentage	60	80	100

Table 2. Design of Experiment (DoE)

Experiment Number	Layer Thickness (mm)	Printing Speed (mm/sec)	Infill Percentage (in percentage)	Surface Roughness (in microns)	S/N Ratio Values obtained after analysis
1	0.14	20	60	2.1875	-6.7989
2	0.14	20	80	2.0250	-6.1285
3	0.14	20	100	2.1325	-6.5777
4	0.14	30	60	2.1850	-6.7890
5	0.14	30	80	2.1750	-6.7491
6	0.14	30	100	2.5750	-8.2155
7	0.14	40	60	2.7250	-8.7073

8	0.14	40	80	2.6550	-8.4812
9	0.14	40	100	2.7475	-8.7787
10	0.17	20	60	2.1875	-6.7989
11	0.17	20	80	2.1925	-6.8187
12	0.17	20	100	2.1325	-6.5777
13	0.17	30	60	2.3725	-7.5041
14	0.17	30	80	2.1750	-6.7491
15	0.17	30	100	2.5750	-8.2155
16	0.17	40	60	2.7250	-8.7073
17	0.17	40	80	2.6550	-8.4813
18	0.17	40	100	2.7475	-8.7788
19	0.20	20	60	2.7225	-8.6994
20	0.20	20	80	2.8250	-9.0204
21	0.20	20	100	2.9750	-9.4697
22	0.20	30	60	2.5700	-8.1987
23	0.20	30	80	2.6525	-8.4731
24	0.20	30	100	3.1450	-9.9524
25	0.20	40	60	3.6575	-11.2637
26	0.20	40	80	3.7875	-11.5671
27	0.20	40	100	3.5750	-11.0655

Fig. 3. XFAB 200 3D Printer

Fig. 4. 3D printed PLA specimen (Experiment no 27)

The Material used for experimentation was Biomedical Grade Polylactic acid (PLA). PLA is a biodegradable and biocompatible polymer generally used for tissue regeneration and body implants. It is non-toxic in nature. The 3D prototype CAD model was created using Fusion 360 (3D modeling software), having a diameter of 6 mm and a height of 12 mm. Once the CAD model of the prototype was made, it is then sliced into the slicing software where the programming is done in G codes, and it is further given to the printer XFAB 200 3D Printer (Fig. 3.) to print, and finally, the PLA specimen was fabricated by the 3D printer (XFAB 200) that specimen is shown in Fig. 4.

The surface roughness of each specimen was determined using the Mitutoyo roughness tester, as shown in Fig. 5. For every specimen, four readings of surface roughness were noted, and an average of four readings was calculated. The obtained average values of surface roughness were optimized using the Taguchi method. A measure of robustness is used in Taguchi designs to discover control elements that minimize variability in a product or process by limiting the influence of uncontrolled causes (noise factors). Smaller - the - best: A characteristic with a specific targeted lower value is used for surface roughness while determining S/N ratio values. The equation for S/N ratio for smaller the better characteristic is given below-

$$S/N = -10 * \log(\Sigma(Y^2)/n)) \dots\dots\dots\dots\dots\dots (1)$$

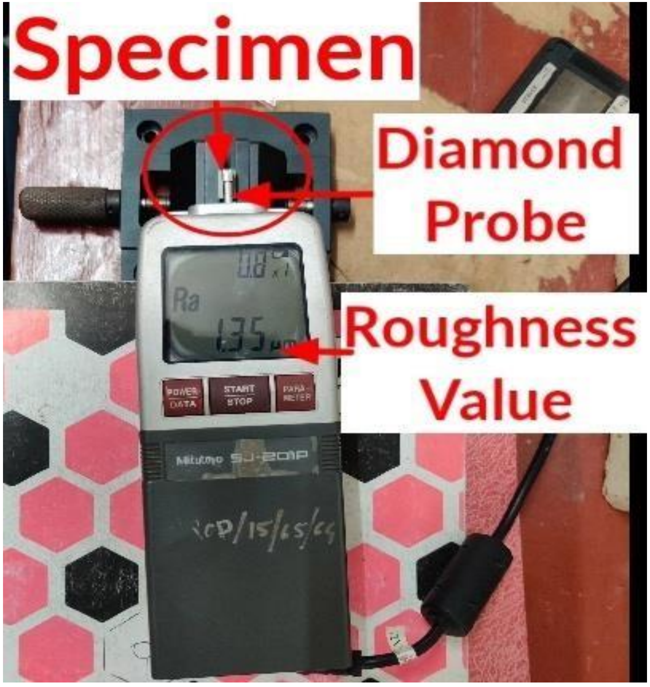

Fig. 5. Mitutoyo Roughness Tester

3. Results and Discussion

Minitab 20 software was used for the analysis. The main effects plot and interaction plots for S/N ratios were plotted for surface roughness as a response variable using lower the better characteristics, as shown in Fig 6 and 7. A higher S/N ratio value is always recommended to achieve the optimum results irrespective of the characteristics of the response variable. Results showed that the optimum values were 0.14 mm of layer thickness, 20 mm /sec of printing speed, and 80% of infill percentage, which were giving the lowest surface roughness value. The infill percentage was least the significant among all process variables Those optimum values were provided by experiment number 2 of the orthogonal array, which had an S/N ratio value of -6.1285, as shown in table 2, which was the highest among all 27 experiments and had the lowest surface roughness value, i.e., 2.0250 microns. In contrast, experiment number 26 (0.20 mm of layer thickness, 40 mm /sec of printing speed, and 80% of infill percentage) had the lowest S/N ratio value of -11.5671, which had the highest roughness value of 3.7875 microns.

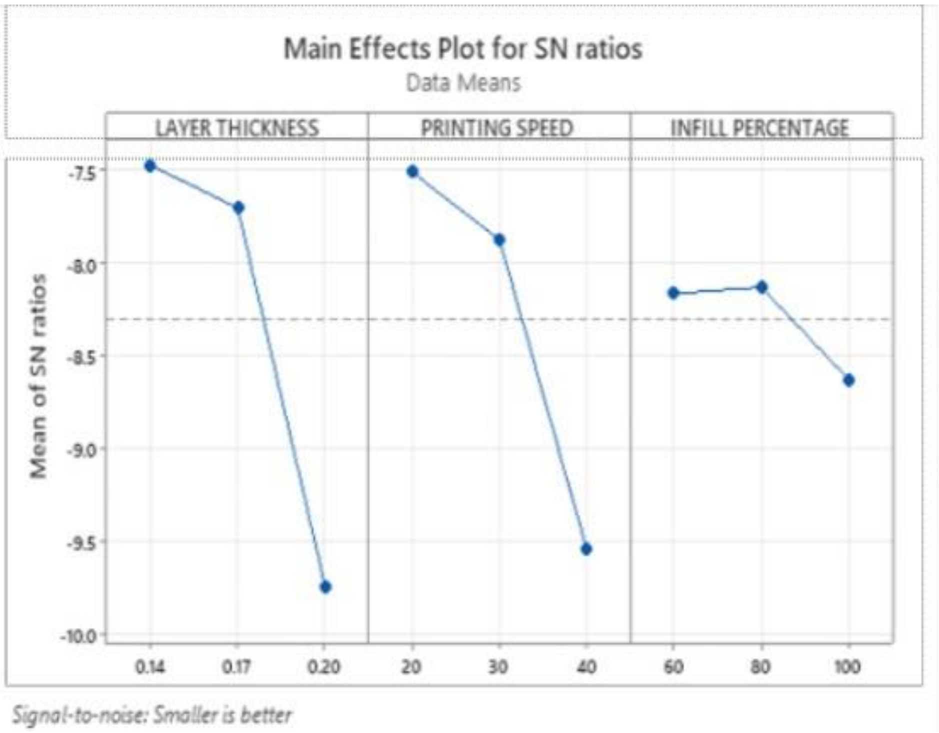

Fig. 6. S/N Ratio plot for Surface roughness

We have used the L27 full factorial design rather than the L16 orthogonal array as used by Altan et al. to get more clarity of results. Most researchers suggested that a lower layer thickness was important to get good surface quality followed by printing speed which was in close agreement with our results. A porous cylindrical-shaped specimen was used in our experimentation rather than a solid cylindrical specimen as used by Perez et al.[26] as results showed lower values of surface roughness in our experimentation than in solid cylindrical specimens, but it was difficult to record the roughness of side surface because of pores present on specimens as the roughness tester requires a flat surface with no pores to record the surface roughness values.

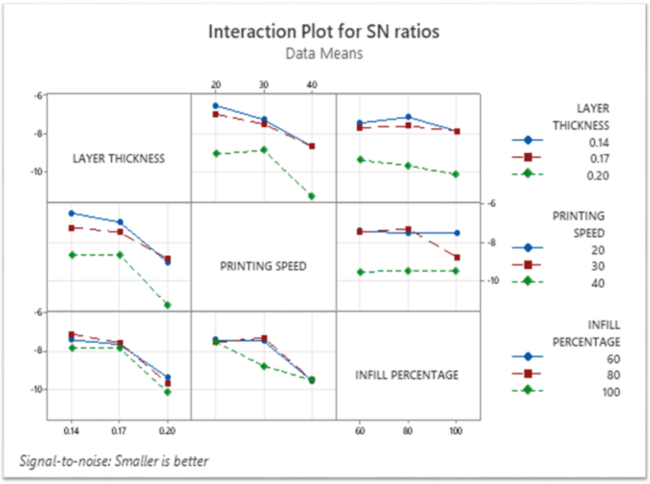

Fig. 7. Interaction plot for surface roughness

The response table for S/N ratios are shown in Table 3 showed that layer thickness has the highest delta value of 2.276, followed by printing speed of 2.027, and the lowest delta value was observed in infill percentage, which was 0.497. Response Table showed that layer thickness had the highest rank (most influencing), i.e., rank

1, followed by printing speed (second most influencing) and infill percentage.This implies that the layer thickness was having a substantial impact on the surface quality of additively manufactured FDM built parts.

ANOVA was further done to test the significance of process variables. The 95% level of confidence was used with two sided tests. ANOVA analysis in Table 3 showed that p-value for layer thickness and scanning speed was below 0.05, stating that both parameters were influencing the 3D printing process. In contrast, the infill percentage was having p-value of 0.05, which demonstrated little significance in process-parameter optimization.

Table 3. Analysis of Variance for S/N ratios

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Layer Thickness	2	29.0936	29.0936	14.5468	186.74	0.000
Scanning Speed	2	22.1827	22.1827	11.0914	142.38	0.000
Infill Percentage	2	1.6665	1.6665	0.8333	10.70	0.005
Layer Thickness*Scanning Speed	4	1.5367	1.5367	0.3842	4.93	0.027
Layer Thickness*Infill Percentage	4	0.4688	0.4688	0.1172	1.50	0.288
Scanning Speed*Infill Percentage	4	2.2851	2.2851	0.5713	7.33	0.009
Residual Error	8	0.6232	0.6232	0.0779		
Total	26	57.8566				

P-values for model coefficients of the S/N ratio also showed the significance of levels of each parameter and their interactions, as shown in Table 4. Layer Thickness of 0.14 and 0.17 mm had a p-value less than 0.05 indicating its significance for the process. Scanning speed levels of 20 and 30 mm/sec were also less than 0.05 marking their influence on the printing. This suggested that low levels of both scanning speed and layer thickness should be provided in order to have better results.

Table. 4. Estimated Model Coefficients for S/N ratios

Term	**Coef**	**SE Coef**	**T**	**P**
Constant	-8.28030	0.05371	-154.157	0.000
Layer Th 0.14	0.81070	0.07596	10.672	0.000
Layer Th 0.17	0.65455	0.07596	8.617	0.000
Scanning 20	0.84805	0.07596	11.164	0.000
Scanning 30	0.40843	0.07596	5.377	0.001
Infill P 60	0.11725	0.07596	1.544	0.161
Infill P 80	0.22821	0.07596	3.004	0.017
Layer Th*Scanning 0.14 20	0.11980	0.10743	1.115	0.297
Layer Th*Scanning 0.14 30	-0.19009	0.10743	-1.769	0.115
Layer Th*Scanning 0.17 20	0.04586	0.10743	0.427	0.681
Layer Th*Scanning 0.17 30	-0.27230	0.10743	-2.535	0.035
Layer Th*Infill P 0.14 60	-0.07942	0.10743	-0.739	0.481

Layer Th*Infill P 0.14 80	0.12173	0.10743	1.133	0.290
Layer Th*Infill P 0.17 60	-0.16164	0.10743	-1.505	0.171
Layer Th*Infill P 0.17 80	0.04778	0.10743	0.445	0.668
Scanning*Infill P 20 60	-0.11743	0.10743	-1.093	0.306
Scanning*Infill P 20 80	-0.11852	0.10743	-1.103	0.302
Scanning*Infill P 30 60	0.25735	0.10743	2.396	0.043
Scanning*Infill P 30 80	0.31983	0.10743	2.977	0.018

4. Conclusions

Surface roughness values (Ra) fluctuated between 2.0250 microns (lowest) to 3.7875 microns (highest).S/N Ratio and Interaction plots for surface roughness showed that layer thickness was the most promising process parameter, followed by printing speed. Lower levels of layer thickness and printing speed were responsible for getting a good surface quality of the additively manufactured component. Surface roughness was more a function of layer thickness rather than printing speed and infill percentage. The filling ratio was the least influencing process parameter among all. Finally, tuning the right parameters will give less surface roughness. The staircase effect leads to the poor surface quality of FDM build parts. A low layer thickness can aid to lessening the staircase effect on printed parts, which in turn will give a better surface finish. Even though getting lower values of surface roughness in porous specimens, it is difficult to calculate the roughness values as the roughness tester requires a flat surface to give proper readings. ANOVA results showed that p-values for layer thickness, scanning speed, and infill percentage were 0.000, 0.000, and 0.050. ANOVA demonstrated that layer thickness and scanning speed were significant process parameters.

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