E3S Web of Conferences **399**, 03003 (2023) https://doi.org/10.1051/e3sconf/202339903003
ICONNECT-2023

Optimization of the Printing Parameters to Improve the Surface Roughness in Fused Deposition Modeling

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Abstract. A better surface finish is an essential requirement of any component in particular medical components. The recent development in additive manufacturing technology produces components with a good surface finish. However, the optimization of process parameters helps to achieve a better surface finish. This paper focuses on the optimization of printing parameters of the surface roughness of a flat object developed from an FDM printer. FDM (Fused Deposition Modeling) is a layer-by-layer deposition process to develop 3D objects. It uses solid-state material (Filament) to print the product by melting and depositing the material on the printing bed. Several factors in the FDM process can affect the product's quality. The parameters such as printing temperature, bed temperature, printing speed, fill density, layer thickness, and air gap influence the quality of the printed products. This investigation has considered printing temperature, layer height, and printing as process parameters. In addition, the parameter affecting the printed object's surface finish is determined using ANOVA optimization and S/N ratios. PLA (Polylactic Acid) is taken as study material which is one of the feedstocks used in polymer filament and finds its applications in implant printing and medical tools.

1 Introduction

Rapid prototyping is a method that uses multiple manufacturing processes, such as 3D printing, CNC machining, and injection molding, to rapidly and effectively build physical models or prototypes of a product or design. Fast prototyping aims to shorten product development, minimize expenses, and enhance product design [1]. Rapid prototyping is creating a 3D model of a product or concept utilizing Computer Aided Design (CAD) application software This 3-Dimensional model design is then used to create a prototype utilizing various production processes, including 3D printing, which is popular due to its speed and versatility. A design may be manufactured in a matter of hours using 3D printing, allowing designers to test and iterate on their ideas fast and efficiently. In addition, it helps

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*Corresponding author: logeshk9078.sse@saveetha.com to enhance the robustness of the design process and optimize the duration of the R&D process [2]. It has been used in various industries to improve productivity by reducing issues and the fastest market implementation of the product.

Additive Manufacturing (AM) is a part of Rapid prototyping, primarily used to prepare product prototypes and to produce the direct product for various applications. Additive Manufacturing is colloquially termed a 3D printing method involving the construction of three-dimensional items by adding layers of material rather than removing material, analogous to traditional manufacturing procedures. It enables the production of complicated geometries and customized designs, which are tedious to produce using standard manufacturing processes. This process has several advantages over traditional Manufacturing, and it can Additive Manufacturing can create complex shapes and geometries, which is impossible through conventional manufacturing processes [3]. The AM method is employed in a variety of applications (aerospace, automobile, etc.) and also for medical and biomedical applications. The materials used in AM techniques are liquid, solid, and powder [4].

Fused Deposition Modeling (FDM) is an AM method that employs solid-state filament material and it is shown in Fig 1. It produces complicated geometric structures with great precision and resolution [5].

The procedure consists of three significant steps:

1.1 Material Preparation

The FDM printer is equipped with a spool of thermoplastic filament inserted into the printer. The filament must be heated to its melting point, which varies depending on the material but is generally between 180 and 260 degrees Celsius.

1.2 Printing method

A nozzle extrudes filament in a melted state, which is subsequently layered onto a build platform, following a computer-programmed route. Each deposited layer solidifies and merges with the preceding layer to form a solid item.

1.3 Post processing

Printed materials can remove from the building platform after the completion of the printing process. However, the final product may require extra post-processing, such as sanding or painting, to attain the desired finish.

FDM produces the 3D object with absolute resolution and accuracy. Therefore, surface roughness is one of the properties needed for quality products. Surface roughness refers to the texture of the printed object’s surface and may be affected by the parameters like layer thickness, printing temperature, printing speed, printing orientation, and filament type.

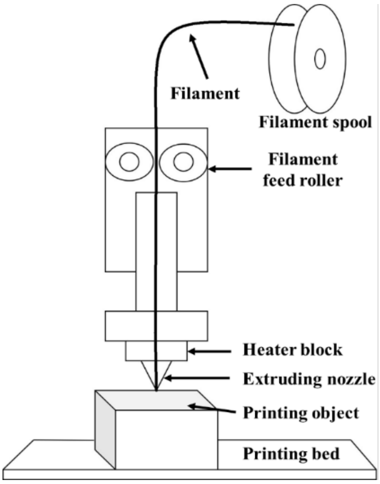

Fig. 1. FDM process.

In FDM printing, layer height refers to the height of each printing layer above the prior layer. The surface irregularity of the printed item may be affected by the layer height since thicker layers result in an irregular surface[6]. However, since the thick layers have noticeable defects or irregularities, thinner layers are preferred since they produce a smoother texture.

Printing speed is another aspect that might influence the surface irregularity of FDM printed objects. Because the printer may need more time to deposit and smooth each layer of material, faster printing rates might result in a rougher surface. Slower printing rates may yield a smoother surface since the printer has more time to deposit and smooth each layer[7].

The filament used in the FDM process can also affect surface roughness. PLA, for example, is recognized for generating smoother surfaces than other filaments like ABS. Because PLA has a lower melting temperature and is less prone to warping, the surface quality is more uniform and smoother. Printing temperature has an effect on surface roughness when it is less than the filament material melting temperature. It makes an improper deposit of materials on the building plate. It may form surface irregularities, so the required temperature can achieve the proper surface roughness of a 3D object. To achieve a smooth surface finish in FDM printing, the layer height, printing speed, printing orientations, printing temperature, and filament type must all be carefully considered. Optimizing the above settings will reduce surface roughness and produce high-quality, visually appealing printed products. Many parameters are critical in the FDM process, predominantly affecting surface roughness quality[8].

FDM-printed objects are influenced by their printing parameters. Ali et al. predicted the dynamic mechanical characteristics of the printed structure. For evaluation reasons, many elements such as air gap, raster angle, and build orientation were changed, and an Artificial Neural Network (ANN) model was constructed based on this design, with the accuracy increased by 5% [9]. Peng and Yan also examined surface roughness and consumption of energy. Definable structures appeared after modifying criteria such as infill ratio, printing speed, essential process parameters, and layer height on three different printers. The study found that layer height is the most significant component in achieving higher surface quality [10].

Finally, Altan et al. investigated how process factors affect PLA surface irregularity and tensile strength. Specimens were created using nozzle temperature, printing speed, and, layer height following ASTM standards and a Taguchi L16 test plan. According to the authors, layer height and printing speed are major determinants of surface irregularity. [11]. Wankhede et al. investigated surface irregularity when factors such as build time on the platform, infill density, and layer height were changed. The Taguchi L9 OA technique was used to optimize the procedure, and it was determined that layer height was the most significant factor [12]. Chohan et al. applied the Design of experiments and ANOVA (Analysis of Variance) on 3D-printed objects using FDM with vapor smoothing. Six parameters were obtained through it and determined using the Buckingham-Pi theorem in this experiment; it takes several vapor smoothing cycles to discover [13]. Wang et al. By adjusting the resin and nozzle temperature settings, printing speed, and layer height, we were able to create a heat-resistant 3D printing model. Several constructions were built with and without resin, and a surface roughness test was performed. This type has been demonstrated to offer a higher surface quality[14].

This study used Taguchi's optimization approach with the L9 orthogonal array to identify the best testing configurations for a printing process with three factors and three levels. Printing temperature, layer height, and printing speed were all taken into account in this study since they were discovered to significantly impact the printed object quality. To enhance the surface irregularity of the printed items, An ANOVA optimization approach, as well as Signal-to-Noise (S/N) ratios, were utilized to identify the parameter that influences surface finish. The feedstock used in the study was PLA (Polylactic Acid), a kind of polymer filament typically used in 3D printing.

2 Materials and Methods

In this specific research investigation, the impact of various crucial machine variables, such as nozzle temperature (°C), layer height (mm), and printing speed (mm/s), on the surface irregularity of 3D printed objects was investigated. Development of the nine samples for investigating the impact of these characteristics. All of the constructions had the same infill density of 10%. This study chose PLA as the printing medium because it performed well in various applications[15,16].

The Taguchi Design of experiments L9 OA approach was implemented to create and analyze the various factors for the experiment. The different factors intended for the study are listed in Table-1. In addition, the irregularities of the flat surface were measured using a portable surface roughness tester called "Mitutoyo SJ-410" shown in Fig 2 [17].

Fig. 2. Surface roughness testing machine (Mitutoyo SJ-410).

The specimens were created using a Creality Ender-3 3D printer shown in Fig 3, and their measurements were 40x40x40 mm with a smooth surface and a 30mm cylinder with a 5 mm thicker upon a cube and two sides of the cube, as shown in Fig 3. The specimens were designed through Computer Aided Designing (CAD) software like SOLIDWORKS 2020. PLA was utilized in the production of these components[18].

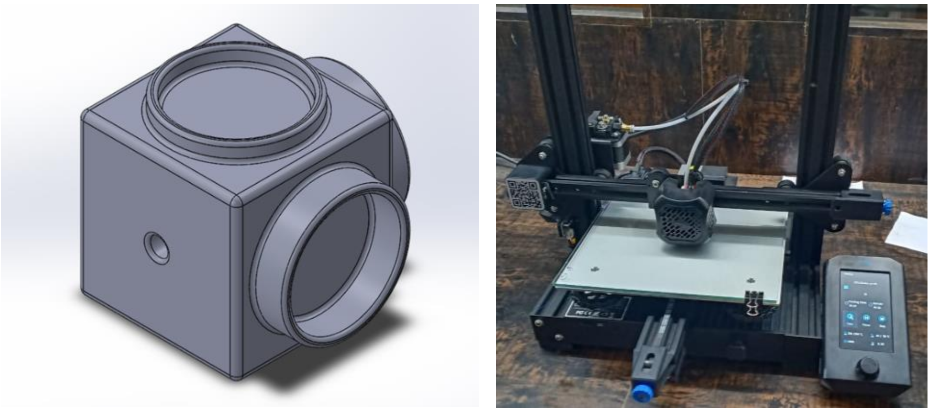

Fig. 3. Printing Object Design and FDM printing machine.

The experiment looked at how different layer thicknesses (0.2mm, 0.35mm, and 0.4mm), nozzle temperatures (190°C, 200°C, and 210°C), and printing speeds (50 mm/s, 75 mm/s, and 100 mm/s) affected the surface of 3D printed structures. However, a flat Surface irregularity was examined to see how these characteristics affected the quality of the final product [8].

Table 1. Printing Parameters.

S.No	Printing temperature (˚C)	Layer height (mm)	Printing speed (mm/s)
1	190	0.2	50
2	190	0.35	75
3	190	0.4	100
4	200	0.2	75
5	200	0.35	100
6	200	0.4	50
7	210	0.2	100
8	210	0.35	50
9	210	0.4	75

3 Results and Discussion

The surface irregularity of the workpiece is determined through a 0.5mm/s probe travel. As a result, the larger the numbers, the more irregular the printed surface. In contrast, a smaller value indicates a smoother surface. The top view flat surface has the highest surface irregularity value of 17.042m, while the side view flat surface has the highest surface irregularity value of 18.509m, according to Table 2 data. Meanwhile, the surface irregularity of the top view flat surface is 5.110µm, and the surface roughness of the side view flat surface is 3.775µm.

Table 2. Surface Irregularity Test Results.

S.No	Printing temperature (˚C)	Layer height (mm)	Printing speed (mm/s)	Mean surface roughness of top view (Ra) µm	Mean surface roughness of side view (Ra) µm
1	190	0.2	50	5.110	14.685
2	190	0.35	75	7.264	18.509
3	190	0.4	100	15.515	10.218
4	200	0.2	75	9.587	10.927
5	200	0.35	100	12.904	11.539
6	200	0.4	50	12.443	3.775
7	210	0.2	100	14.043	5.579
8	210	0.35	50	12.903	5.814
9	210	0.4	75	17.142	6.061

The Taguchi technique was utilized for experimental design and analysis in this work. Nine structures were built to study the consequences of decisive factors including the nozzle temperature, layer height, and printing speed on surface roughness shown in Table 1[19]. The surface irregularity was assessed with the aid of the Mitutoyo SJ-410 portable surface roughness measuring system. The Taguchi Design of Experiment technique was used to design the experiment with L9 orthogonal array approach, and the S/N ratio test was utilized to find the ideal factors values[20,21].ANOVA table was prepared to examine the experimental data and determine the relevant parameters affecting surface roughness[22,23]. The S/N ratio test formula is as follows:

$$S/N = -10\log\left(\frac{\sum Y_i^2}{N}\right) \tag{1}$$

N is the sample count, Y_i is the measured value for the ith sample, and the lower the S/N ratio, the higher the level of performance.

Table 3. Response for S/N Ratios for surface irregularity of top view.

Level	Printing temperature (˚C)	Layer height (mm)	Printing speed (mm/s)
1	-18.40	-18.92	-19.43
2	-21.25	-20.55	-20.51
3	-23.28	-23.46	-22.99
Delta	4.88	4.55	3.57
Rank	1	2	3

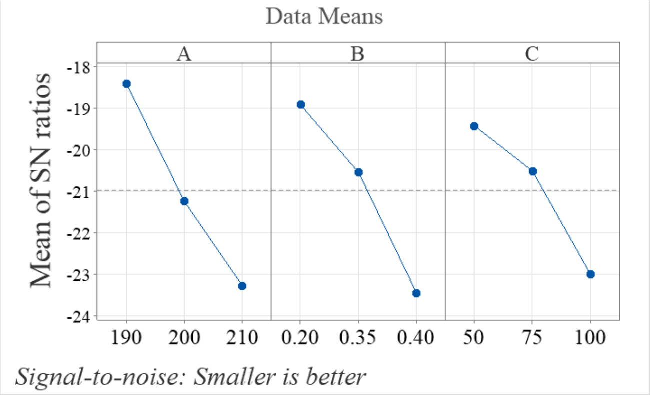

Fig. 4. S/N ratios plot for surface irregularity of top view (S/N: Smaller is better).

Table 4. Response for S/N Ratios for surface irregularity of side view.

Level	**Printing temperature (˚C)**	**Layer height (mm)**	**Printing speed (mm/s)**
1	-22.96	-19.68	-16.72
2	-17.85	-20.63	-20.59
3	-15.29	-15.79	-18.79
Delta	7.67	4.83	3.87
Rank	1	2	3

Fig. 5. S/N ratios plot for surface irregularity of side view (S/N: Smaller is better).

The ANOVA table describes the sources of variation in the experimental data and determines each parameter's % contribution to the total variance. The ANOVA table formula is as follows:

The formula for the Sum of Squares (*SS*):

$$SS = \sum_{i=1}^{n} (Y_i - \bar{Y})^2 \tag{2}$$

The components significance and interactions were then determined using the ANOVA table. The ANOVA table is a tool that breaks down the total variance of the output variable into its constituents due to the variables and their interactions. It enables researchers to discover and optimize the most important elements influencing the output variable.

The ANOVA table contains the Sum of Squares (SS), Mean Square (MS), Degrees of Freedom (DoF), F-value, and p-value. The SS represents the variance generated by each element and its interactions, whereas the DoF represents the degrees of freedom related to each factor.

The formula for Mean Squares (MS):

$$MS = \frac{SS}{DoF} \tag{3}$$

The F-value is the ratio of the MS of each factor to the error MS. If the null hypothesis is true, the p-value is the probability of getting an F-value as large as the one observed. If the p-value is less than the significance level and the factor is judged significant, the null hypothesis is rejected.

Table 5. ANOVA for surface irregularity of top view.

Source	**DoF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Printing temperature (˚C)	2	36.040	36.040	18.020	9.25	0.098
Layer height (mm)	2	31.844	31.844	15.922	8.18	0.109
Printing speed (mm/s)	2	20.046	20.046	10.023	5.15	0.163
Residual Error	2	3.895	3.895	1.948		
Total	8	91.826				

Table 6. ANOVA for surface irregularity of side view.

Source	**DoF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Printing temperature (°C)	2	91.43	91.43	45.713	7.74	0.114
Layer height (mm)	2	39.38	39.38	19.689	3.33	0.231
Printing speed (mm/s)	2	22.48	22.48	11.238	1.90	0.344
Residual Error	2	11.81	11.81	5.906		
Total	8	165.09				

For the top and side views of the printed sample, Tables 3 & 4 show the reaction to the signal-to-noise ratios (S/N ratios) for surface roughness. According to how they affected this study, these tables rank the parameters. Both tables clearly show that the printing temperature has a considerable influence over the other factors, printing speed, and layer height. Regarding the surface irregularity S/N ratio on the top and side views of the printed sample, the figures (Fig 4 & 5) show the significant parameter values for all the chosen parameters.

The top and side views of the printed sample's surface roughness were the subject of an ANOVA analysis included in the study and shown in Tables 5 & 6.

Given the three factors, the degree of freedom in the ANOVA analysis is assumed to be two. Concerning equation 2, the sum of squares is then determined. The F-value is then determined using the ratio of the MS of each component to the error mean squares, taking into account equation 3 along the way. By using the probability table, the p-value concerning the F-value is determined. The p-value in this study indicates that not all parameters are statistically significant, although this may be fixed by extending the length of the experimental runs. The printing temperature is thus displaying a better effect than the other two factors in both the top and side views of the printed sample when the p-values for the three parameters are compared. The optimization research for surface roughness is conducted by Mohd Sazli Saad et al. in their work, and the parameters considered include printing temperature, printing speed, layer height, and outer shell speed [24]. Printing factors taken into account by Peng Wang and colleagues in their work include nozzle temperature, printing speed, layer height, deposition road width, as well as printing bed temperature [25, 26]. In this study, optimum parameters are identified for enhanced surface quality.

4 Conclusions

During the FDM process, surface irregularity is one of the essential factors, and it is investigated in this research. Taguchi's experiment design makes the test runs through L9 orthogonal array. From the S/N ratio for the top view surface finish, the printing temperature is influenced more, and the layer thickness and printing speed are affected less. Same as it is the S/N ratio for the side view surface finish, the printing temperature is influenced more, and then the layer thickness and printing speed are affected less. The S/N ratio plot shows better-performed parameters: the top view is 200°C,0.35 mm, and 75 mm/s, and the side view is 200°C,0.2 mm, and 100 mm/s. ANOVA table developed for both (side view and top view) surface roughness show parameters are not significant but with the p-value compared with the other parameters to find the most effective one. Through this, the printing temperature shows the lowest p-value than other parameters. So, the printing temperature is more influenced than the other two parameters (Layer thickness and printing speed). L9 OA took the test runs, and nine experimental runs were performed through this research. If the L27 OA is used, 27 experimental runs can be performed, and the significance can be improved.

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