EXPERIMENTAL AND STATISTICAL EXAMINATION OF THE SURFACE QUALITY OF ORGANIC PLANT-BASED FILAMENT MATERIALS USED IN 3D PRINTERS

Ahmet İpekçi

Dr. Engin Pak Cumayeri Vocational High School, Düzce University, Düzce, Türkiye

Abstract

Nowadays, additive manufacturing methods have started to become popular. The fact that it does not produce waste material such as machining methods and does not require molds as in classical plastic production methods makes these methods popular. In addition, the variety of materials used is increasing. Polylactic acid (PLA) material, produced from commonly used materials such as corn starch, is a plastic produced from organic materials and harmless to humans and the environment. In addition, the newly produced STH-coded material is produced on an organic basis and is harmless to the environment and humans. The advantages of STH material over PLA material are that it can work at higher temperatures and increase mechanical strength. In additive manufacturing methods, final product quality is generally controlled in terms of surface roughness. Because, in additive manufacturing, the molten material covers the surface in the form of a pattern, creating a surface with a certain roughness. For this reason, in this study, cube-shaped samples were produced by using PLA and STH materials, selecting three different variable production parameters (material type, filling shape, and extruder temperature), and determining a total of 18 test parameters at three different levels. After production, surface roughness values were measured from the upper surface. In line with these values, the Taguchi L_{18} experimental setup was applied and the best production parameters were examined in terms of surface quality. An equation that will predict the surface quality to be obtained with the selected parameters was derived through regression analysis. As a result of this study, the surface quality can be reduced below 1 micron surface roughness values in additive manufacturing and the surface quality is almost close to plastic injection molding.

Keywords: *additive manufacturing, surface roughness, Taguchi, PLA, STH, optimization*

1. INTRODUCTION

Today, there is almost no sector where additive manufacturing methods are not applied. These effects are more common, especially in areas where plastic raw materials are preferred. The materials used in the additive manufacturing method are commonly thermoplastic-based. PLA and Acrylonitrile Butadiene Styrene (ABS) materials are the most well-known examples of these. Here, since the use of ABS material has some environmental adverse effects related to the release of harmful gases and decomposition in nature, PLA material is produced from biomaterials such as corn starch, allowing the use of materials suitable for both the environment and health in the sector. In this way, PLA material can be used in many different applications, especially in the medical sector. For example, it is preferred in tumor therapeutics, dental surgery, coronary stents, graft filling, vascular delivery, and meniscus repair applications because it is biocompatible [1].

PLA material provides great success in terms of biocompatibility. However, it lags behind other thermoplastic materials such as ABS in terms of other desired properties. Examples of these features include low surface quality, poor mechanical properties, long production times, and high energy consumption [1].

In another recent study, the strength and surface roughness values of samples produced using the rectilinear filling method of PLA material with different layer thicknesses, with the top pattern changing by 0°, 45°, and 90°, were examined. In measurements made along the direction of the toolpath, the lowest surface roughness was observed to be 0.51 µm [2].

In a similar study, as a result of production with layer thicknesses between 0.05 and 0.25 mm, increasing by 0.05 mm with PLA material and with a completely flat filling pattern, the most optimum production time and surface roughness in the vertical direction was obtained with a layer thickness of 9.1 µm and 0.15 mm [3].

In another recent study, the dimensional accuracy and surface quality of 3D printing samples made with PLA material were checked under variable conditions depending on the printing speed, filling rate, and nozzle temperature. The optimum recommended printing parameters with a margin of error of 7.5% are 54 mm/min printing speed, 50% fill rate, and 240° nozzle temperature. In this case, it is said to provide 20 µm surface quality and 0.17 mm measurement tolerance [4].

In a similar study, production was made from PLA material by varying the layer thickness, filling density, and extruding temperature values. Tensile tests and surface roughness measurements were carried out on these produced samples. In consequence of statistical calculations, 0.15 mm layer thickness, 55% filling density, and 210° extruding temperature values are recommended as optimum in terms of surface quality. At these optimum values, the measured surface roughness values are given as 9.15 µm [5].

In another study, it is said that the surface quality of PLA material was examined according to less examined parameters, and the surface quality of the internal surfaces was measured with the help of a contact probe. The parameters considered as effective variable parameters here are; table temperature, fan operating rate, printing speed, extruding temperature, and number of perimeters. As study results, it is said that the surface quality increases as the wall thickness increases. It is also said that as the printing speed decreases, the inner surface quality also decreases [6].

In another study for PLA material, a machine learning algorithm combining Transfer Learning-based decision trees was tested to analyze the effects of 3D printing process parameters on surface quality. The results indicate that the recommended model can acquire high precision above 0.9900, indicating that layer height can significantly impress the surface quality as an importance score of 0.626 [7].

In general, in production using ABS, PLA, Power ABS, and STH materials, surface raster angles of 0°, 45°, and 90° were selected as variable parameters. Surface quality was measured on the top surface in two directions. It is said that in most cases, STH material gives the lowest quality and obtains results close to PLA material [8].

In a study examining the surface quality of STH material experimentally and statistically, layer thickness, printing speed, and extrusion width were selected as effective and variable parameters, similar to the parameters in other studies. Surface roughness measurements were carried out in all three axes. It is said that 0.1159 mm layer thickness, 113.6359 mm/s 3D printing speed, and 0.3550 mm extrusion width are the recommended effective values for surface quality in STH material [9].

Although PLA material is widely used and its parameters have been optimized through experiments in terms of many parameters, the production parameters and production quality of the STH-coded biomaterial, which is very new compared to PLA material, are not yet widely known and not many articles on this material are included in the literature. In addition, PLA and STH materials should be considered together comparatively since they are both biomaterials. For these reasons, in this study, the materials and parameters that provide optimum parameters and surface quality with the Taguchi optimization method are discussed by producing test samples from PLA and STH materials with different surface filling shapes and different nozzle temperatures.

2. MATERIALS AND METHODS

2.1. Materials

Within the scope of the research, organic plant-based filament materials were preferred because they do not cause pollution to the environment and do not contain materials harmful to human health. Examples of these materials include the most well-known and widely used PLA material and the new STH-coded material derived and produced by ABG. For these reasons, PLA and STH materials were used in the study. The properties of the materials used, given by the manufacturer, are given in Table 1.

Properties	Unit	PLA	STH
Tensile Strength	kg/cm^2	590	407
Tensile Modulus	kg/cm^2	33000	41000
Tensile Elongation	%	4	50
Flexural Modulus	kg/cm^2	23000	35000
Flexural Strength	kg/cm^2	550	770
Rockwell Hardness	-	75	75
Izod Impact Strength	kg.cm/cm	16	25
Vicat Softening Temperature	°C	58	85
Specific Gravity	-	1.24	1.22
Molding Shrinkage	%	0.2-0.4	0.2-0.5
Melt Flow Rate	g/10 min.	27	21

Table 1. Mechanical, physical, and thermal properties of materials [10, 11].

Source: Compiled from ABG Filament website, materials datasheets, April 2024.

When the technical properties of the materials are examined, it is observed that the flexibility of the STH material has increased significantly compared to the PLA material, its impact resistance and flexural strength have increased, and the Vicat softening temperature value has increased significantly. In this way, STH material can be used in many areas where it is not possible to produce with PLA material, thanks to these developed features.

2.2. Production Method

After material selection, the Fused Deposition Modeling (FDM) method, which is among the additive manufacturing methods, was chosen as the production method. The common and generally used name of this method can be given as 3D printing. The occasion for selecting this method is that it is suitable for use with plastic materials, is widely used today, and is suitable for testing variable production parameters. The 3D printing parameters used in the study are given in Table 2 below.

Properties	Unit	Value
Filling Rate	%	30
İnfill Shape	-	Rectilinear
Nozzle Diameter	mm	0.4
Extruding Temperature	°C	190 – 200 - 210
Top Solid Layer	-	3
Top Solid Layers Filling Shape	-	Concentric Archimedian Chord Octagram Spiral
Perimeter Number	-	3
Layer Thickness	mm	0.20

Table Temperature	°C	70
Extrusion Width	mm	0.40
Printing Speed	mm/s	80

Table 2. Printing parameters for sample production.

The Top solid layer filling shape parameter given in Table 2 is variable and is independent of the filling shape that creates the inner filling in the printing process. Here, inner filling shape and filling ratio are selected as fixed parameters as general production parameters. The top outer surface filling shape is a variable parameter as it directly affects the outer surface shape and quality. Here, octagram spiral, archimedian chords, and concentric filling shapes were preferred as external face-filling shapes that would obtain the smoothest shape and provide symmetrical filling form all directions. These filling forms are given in Figure 1.

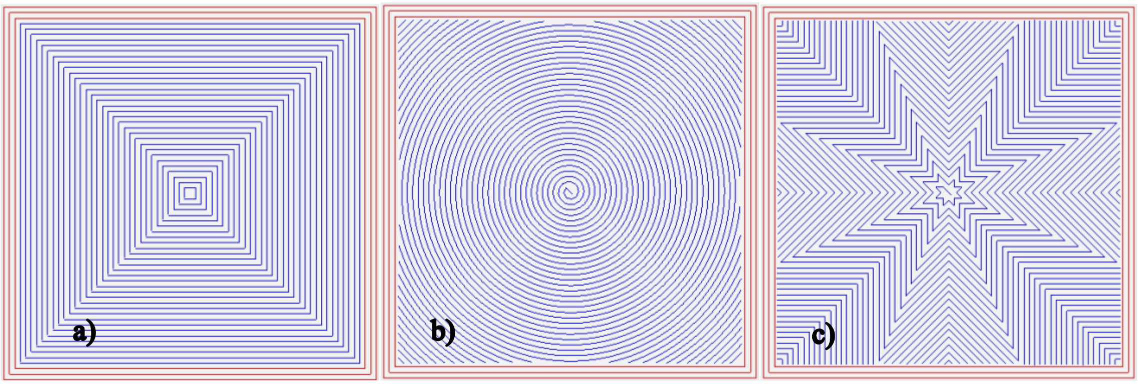

Fig. 1. Top solid layer filling shapes – a) concentric, b) archimedian chords, c) octagram spiral.

2.3. Experimental Setup

After determining the material and printing parameters, it is necessary to create an experimental setup. Since the optimization method also has an effect on this, the optimization method was determined as Taguchi L_{18} at this point. In this case, according to the Taguchi method, the layout containing a total of 18 experiments with variable parameters 2^1 and 3^2 is given in Table 3.

Sample No	Material	Top Solid Layer Filling Shape	Extruder Temperature
1	PLA	Concentric	190
2	PLA	Concentric	200
3	PLA	Concentric	210
4	PLA	Archimedian Chords	190
5	PLA	Archimedian Chords	200
6	PLA	Archimedian Chords	210
7	PLA	Octagram Spiral	190
8	PLA	Octagram Spiral	200
9	PLA	Octagram Spiral	210

10	STH	Concentric	190
11	STH	Concentric	200
12	STH	Concentric	210
13	STH	Archimedian Chords	190
14	STH	Archimedian Chords	200
15	STH	Archimedian Chords	210
16	STH	Octagram Spiral	190
17	STH	Octagram Spiral	200
18	STH	Octagram Spiral	210

Table 3. Sample coding and experimental setup.

2.4. Printing Samples

After determining the material selection, variable parameters and production parameters for the study, the 3D design of the cube with dimensions of 20x20x20 mm, selected as a sample, was made in the Solidworks program. Then, this 3D drawing was saved in STL format to extract production codes for the printer. The recorded data was opened in the Slic3r program and the production Gcode file was derived after the selected production parameters were specified. The derived gcode files were transferred to the printer with the help of an SD card and each test sample was produced under equal conditions. Figure 2 shows pictures of the production.

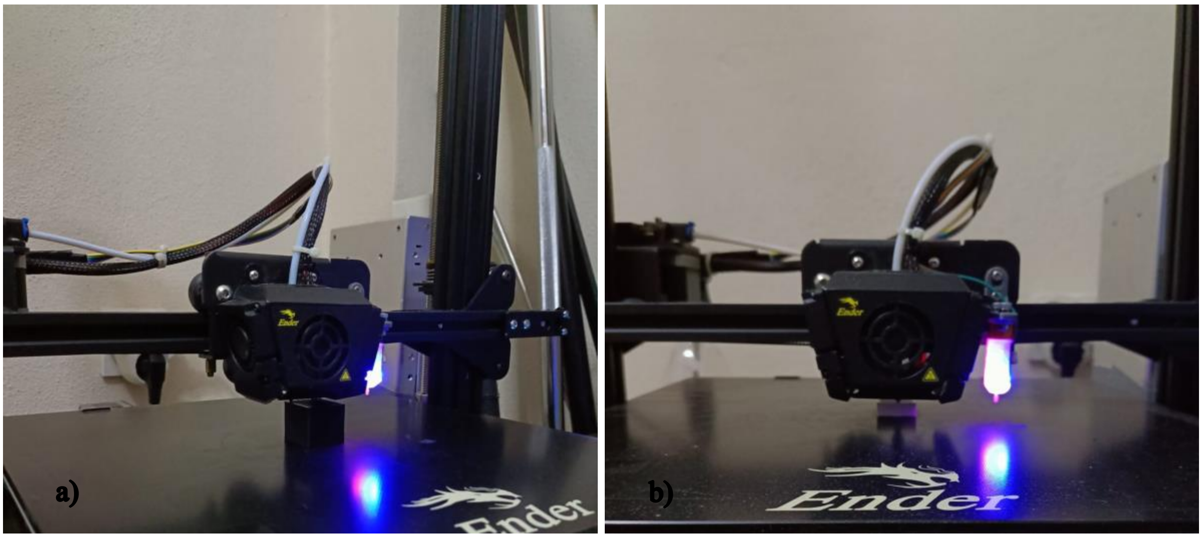

Fig. 2. Printing sample cubes – a) STH material, b) PLA material.

2.5. Surface Roughness Measurements

Afterward the production samples were completed, each sample was subjected to separate surface measurements along the 4 edges of its top surface, as indicated in Figure 3a. Then these measurements were averaged. All measurements were taken under equal conditions with a PCE-RT 2000 portable surface roughness device. Ra arithmetic average measurement method was preferred as the surface roughness measurement method. Additionally, surface roughness measurements were carried out in accordance with TS EN ISO 21920-2 standard.

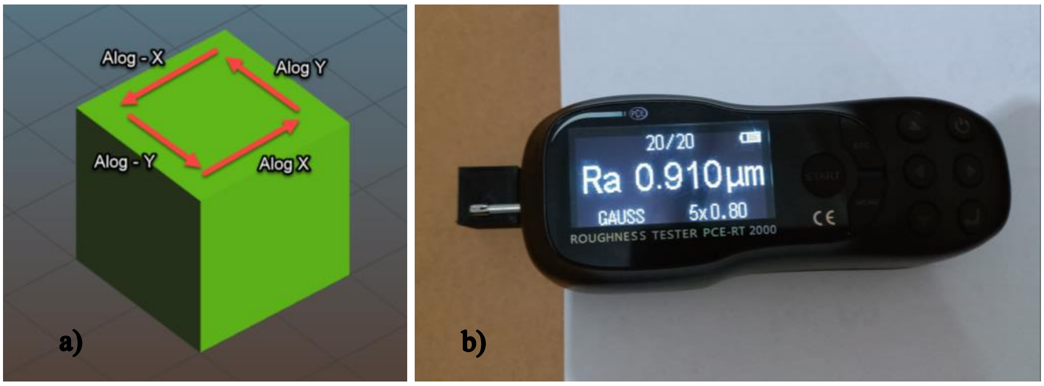

Fig. 3. a) Expression of the upper surface measurement axes b) Surface roughness measurement.

2.6. Optimization

After all surface roughness measurements are obtained, it is time to perform statistical calculations under favor of these data. The chosen method for optimization is the Taguchi method. This method is generally suitable for parameter optimization with a small number of experiments. Minitab 20 software was used for statistical calculations. At the beginning of the calculations, signal and noise ratios and mean values were first found. Then, analyzes such as analysis of variance and regression analysis were performed respectively.

3. RESULTS

The results such as surface roughness measurements results and anova table, regression equation and signal / noise ratio table made within the scope of the study are discussed in the following headings in this section.

3.1. Surface roughness results

In the study, surface roughness measurements made on the upper surfaces of the samples in 4 different axes and the average of these values are given in Table 4. When these results are analyzed, it is apparent that the lowest surface roughness value for Sample no 2 PLA material is 1.087 µm. In addition, in Sample number 12, the lowest surface roughness value of 0.951 µm is observed for the STH material.

Sample No	**Along +X axis Ra**	**Along +Yaxis Ra**	**Along -X axis Ra**	**Along -Y axis Ra**	**Averaged Ra**
1	1.149	1.200	1.316	1.770	1.359
2	0.848	0.838	1.536	1.125	1.087
3	1.262	1.329	1.991	2.366	1.737
4	1.399	1.356	1.511	1.282	1.387
5	1.619	1.236	1.432	1.279	1.392
6	1.721	1.225	1.422	0.845	1.303
7	4.389	5.837	5.358	5.349	5.233
8	3.744	5.616	3.265	4.780	4.351
9	5.728	5.596	5.351	6.518	5.798
10	0.910	0.826	1.639	1.006	1.095

11	2.080	1.071	1.459	1.104	1.429
12	1.036	1.041	1.042	0.683	0.951
13	1.494	2.650	1.239	1.782	1.791
14	1.167	2.033	1.122	1.379	1.425
15	2.117	1.832	1.294	1.043	1.572
16	4.359	4.250	3.111	3.567	3.822
17	1.960	3.666	3.358	3.533	3.129
18	3.825	4.575	3.619	4.889	4.227

Table 4. Top surface roughness measurement results (µm).

3.2. Optimization results

In statistical calculations for optimization, the standard deviation value in regression analysis and ANOVAcalculations is 0.543745 and R^2 has a safety value of 91.65%. The R^2 value being more than 90% indicates that the margin of error in statistical calculations is low.

After these main calculations are made, signal and noise ratio calculations are given in Figure 4. The signal and noise ratio gives us information to rate the effect of parameters on measured values. Since the smallest surface roughness value indicates the best quality, we will interpret the results obtained in the calculations as smallest is best. As can be seen from Figure 4, the parameters with the smallest numerical value are the levels that give us the lowest surface roughness. These levels are calculated as STH material, Concentric filling shape and 200 °C extruder temperature.

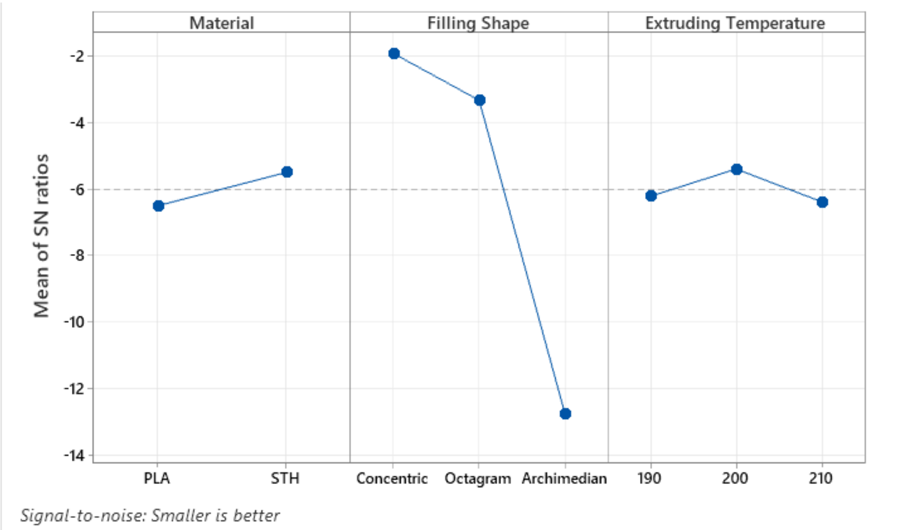

Fig. 4. Main effects plot for signal to noise ratios.

Variance analysis calculations help us calculate the importance of each parameter on surface quality as a percentage. Table 5 shows the calculated values for the variance analysis table. As can be seen from the Contribution tab, the filling shape parameter dominates the surface quality by 87.77% compared to the material and extruder temperature parameters.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Material	1	0.9828	2.31%	0.9828	0.9828	3.32	0.0932639
Filling Shape	2	37.3161	87.77%	37.3161	18.6581	63.11	0.0000004
Extruder Temperature	2	0.6680	1.57%	0.6680	0.3340	1.13	0.3552028
Error	12	3.5479	8.35%	3.5479	0.2957		
Total	17	42.5149	100.00%				

Table 5. Variance analysis results.

In consequence of the regression analysis, a prediction equation was derived for the average surface roughness according to the parameters and levels in the study. The average surface roughness prediction equation is given in Equation 1.

$$\text{Averaged Surface Roughness Ra} = 2{,}394 + 0{,}234\ \text{Material\_PLA} - 0{,}234\ \text{Material\_STH} - 1{,}117\ \text{Filling Shape\_Concentric} - 0{,}915\ \text{Filling Shape\_Octagram} + 2{,}033\ \text{Filling Shape\_Archimedian} + 0{,}054\ \text{Extruder Temperature\_190} - 0{,}258\ \text{Extruder Temperature\_200} + 0{,}204\ \text{Extruder Temperature\_210} \quad (1)$$

4. DISCUSSION

In the study, surface roughness values decreased to the lowest value of 0.951 µm. The highest roughness value was determined as 5.798 µm. Although 5 µm roughness value was found to be the highest value in our study, it is expressed as the minimum and high quality in additive manufacturing methods by many studies in the literature [12]. In addition, in the literature, rectilinear filling shape is generally preferred as the filling shape in production. The most effective parameter as one of the main outcomes of the study is the filling shape parameter. For this reason, it is understood that the concentric filling method gives better quality results for flat surfaces. Likewise, in a similar surface roughness parameter optimization study using STH material, surface roughness values of 2 - 2.5 µm were obtained on the upper surface in response to the rectilinear filling method [9].

5. CONCLUSIONS

In this research, which was conducted to specify the most effective production parameters in terms of surface quality in the additive manufacturing method with plant-based filament materials, inferences are made on the following issues:

- Each parameter has a certain effect on the surface quality, but when the effect is observed as a percentage, the filling shape parameter is the main effective parameter as it directly determines the shape of the surface.
- As a result of the study, the parameters to be recommended to maximize the overall surface quality according to optimization calculations are; STH material, concentric filling shape and 200 °C extruder temperature.
- With the selected parameters, the highest surface quality was measured as 5.798 µm and the best surface quality was measured as 0.951 µm. Being able to reduce the surface quality below 5 µm without applying any post-processing using the additive manufacturing method meets the expected surface quality values in many areas.

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