

Research Article

Experimental and statistical investigation of the surface quality of 3D printed products using STH filament material

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Abstract

Three dimensional (3D) printers have entered every aspect of our lives. Especially home users use 3D printers in many projects within the scope of do-it-yourself (DIY) projects. In addition, as a control mechanism in the transition from design to production, especially in areas such as prototyping, it almost eliminates the margin of error. However, the types of raw materials that can be used in 3D printing processes are relatively limited compared to other production methods. Features such as suitability for production in layers and rapid solidification come to the fore. Additionally, cooling deformations such as shrinkage also reduce the variety of materials that can be used. ABS, which is the most commonly used thermoplastic material, is also used in 3D printers. However, since ABS material has high cooling deformations such as shrinkage in production, errors occur frequently. This makes the use of the material difficult. In addition, the gases released during production cause discomfort to people. For this reason, PLA material was developed as a biomaterial based on corn starch. Easy to produce, shrinkage and cooling errors are almost non-existent. It is environmentally friendly and there is no gas released during production. However, when using PLA material, certain properties of the products such as abrasion, thermal resistance and hardness are weak in meeting the needs. For this reason, STH filament material was introduced to the market with the aim of developing a material with high thermal stability like ABS and easy to produce like PLA. Just like PLA, STH filament material is also a biomaterial and was developed for industrial use. Compared to ABS material, it is more resistant to impact environments and its thermal resistance is approximately twice that of PLA material. For this reason, in our study, parameter optimization was carried out to optimize the surface quality of 3D printed products using STH material. Layer thickness (0.15 - 0.25 mm), printing speed (60 - 100 mm/s) and extrusion width (0.35 - 0.45 mm) were preferred as variable parameters affecting the surface quality. An experimental setup consisting of 20 experiments was created using the Response Surface Method (RSM), keeping all other parameters constant. The printed

25x25x25 mm cube samples were subjected to surface roughness measurement in 3 axes. According to the results, as a result of statistical calculations, the impact ratios of the effective parameters and the most effective production parameters were estimated.

Keywords: 3D printing, STH filament, RSM, Optimization, Surface Roughness.

1. Introduction

Nowadays, additive manufacturing, which is known as one of the production methods other than traditional machining, has been divided into many branches [1]. Additionally, a specific terminology has been adopted according to ASTM standards [2]. For many businesses and industries, additive manufacturing methods have become the main production method rather than just being used for prototyping to speed things up. To give examples of these sectors, such as jewelry industry, precision casting moldings, surgical planning, medical products, prosthesis production can be mentioned [3 - 6].

Today, the most widely used additive manufacturing method is the Fused deposition modeling method. It is known as 3D printing method. The main reason why the 3D printing method is most widely used is that the molten material forms the volume of the 3D object to be produced in layers through a print head. This means that it does not require any machining or tool consumption. Additionally, there are no complex geometric limitations in production with this method [7]. Since most of the materials used are thermoplastic, production costs can be reduced by using recycled materials [8].

Although the 3D printing method has become widespread in commercial use, there are still many issues open to academic research and development. Especially in the 3D printing process, the product can be given an internal cavity and filling pattern during production. Thus, variable properties can be obtained in products with the same volume and appearance [9]. Additionally, many studies are carried out on issues such as product cost and parameter optimization [10].

Another important issue is the type of material used. Here, specific sectoral needs can be met depending on the plastic derivative that can be used in 3D printing. For example, bioplastic materials are important for human health and the environment in many areas. Such materials are gaining importance, especially in the production of personalized boluses in radiotherapy and in the production of implants in medical applications [11].

The most commonly used 3D printer filament materials are ABS (acrylonitrile butadiene styrene), PLA (polylactic acid) and PETG (polyethylene terephthalate). ABS material is a material known and used in many sectors. However, due to high shrinkage margins, errors occur in production and it produces gases that are harmful to health. Therefore, biocompatible PLA material is produced and used as 3D printing raw material. However, although it is easy to produce, it is insufficient in applications, especially because its

strength, thermal stability and impact resistance are low [12]. For this reason, today a new bioplastic material with the code STH has been derived and is used commercially in the 3D printing industry. It offers higher impact resistance than ABS and almost twice the thermal resistance of PLA. It stands out among 3D printer raw materials with its surface quality and easy printing features [13].

When studies on the surface quality of STH material are searched, very little literature is found since it is a very new type of material. In particular, no studies have been found on the parameters affecting surface quality and the optimization of these parameters. In a study that can serve as an example of the subject, tensile test samples were produced from ABS, PLA, POWERABS and STH materials on the table plane with a raster angle of 0, 45 and 90 degrees. Tensile strength, percentage elongation and surface roughness values of these produced samples were measured in vertical and horizontal directions. Finally, the fracture surfaces were examined with photographs. The 0 degree raster angle generally gave the highest strength. The 45 degree raster angle gave the highest percentage elongation values. The lowest values were obtained in surface roughness measurements made parallel to the raster angle [14].

For these reasons, in this study, samples were produced from STH filament material with different production parameters, and the surface roughness values of these samples were measured in different directions and a statistical study was carried out with the help of the data obtained from the measurements. At the end of this statistical study, the effects of layer thickness, surface roughness and extrusion width parameters on the surface quality of products produced from STH material and the appropriate levels to select for the best surface quality were examined. Thus, it is aimed to contribute to the literature as a reference at a commercial and academic level for those who want to use this material in 3D printing processes.

2. Materials and Methods

2.1. Material Selection

In this study, the main 3D printing parameters and their effects that affect the surface quality of the newly developed STH material, which has not yet been examined in detail in the literature, were examined. The main properties of the STH biomaterial shared by the manufacturer are given in Table 1.

Table 1: Physical, Mechanical and Thermal Properties of STH Filament Material [15]

Properties	Test Method	Unit	Typical Value
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Specific Gravity	ASTM D792	-	1.22
Molding Shrinkage	ASTM D955	%	0.2 – 0.5
Melt Flow Rate	ASTM D1238	g/10 min.	21
Tensile Strength	ASTM D638	kg/cm ²	407
Tensile Elongation	ASTM D638	%	50
Tensile Modulus	ASTM D638	kg/cm ²	41000
Flexural Strength	ASTM D790	kg/cm ²	770
Flexural Modulus	ASTM D790	kg/cm ²	35000
Izod Impact Strength	ASTM D256	kg.cm/cm	25
Rockwell Hardness	ASTM D785	-	75
Vicat Softening Temperature	ASTM D1525	°C	85

2.2. Production Method

After determining the material for the study, the most important criterion is to determine the effective and constant parameters for production. Since we use a 3D printing method, the main production parameters are determined according to this method and material. In order for the production to be error-free, the extrusion temperature and table temperature are determined as constant according to the material properties. In addition, nozzle diameter, perimeter and top solid layer number were kept constant. In addition, the filling rate and filling form were chosen as constant since they change the shape under the surface and affect the quality. The effective parameters when melt pouring the material that affects the surface quality of the outermost layer, printing speed, extrusion width and layer thickness are determined as variable parameters. These selected 3D printing parameters and values are given in Table 2.

Table 2: Selected 3D Printing Parameters

Parameter	Unit	Typical Value
Filling Rate	%	30
Filling Form	-	Rectilinear

Nozzle Diameter	mm	0.4
Top Solid Layer	-	3
Perimeter Number	-	3
Nozzle Temperature	°C	200
Table Temperature	°C	70
Layer Thickness	mm	0.15 – 0.25
Printing Speed	mm/s	60 - 100
Extrusion Width	mm	0.35 – 0.45

2.3. Experimental Setup

With the help of these selected variable parameters, the statistical method required for optimization must be determined and the experimental setup must be created. First of all, among the generally used statistical optimization methods, the Response Surface Modeling (RSM) method was preferred due to its suitability to surface quality and low error rates. Central composite design was selected and the experimental setup and sample quantities required for production were determined with the help of variable parameters. Table 3 contains the experimental setup and sample coding.

Table 3: Experimental Setup and Sample Codes

Sample Code	Layer Thickness (mm)	Printing Speed (mm/s)	Extrusion Width (mm)
S1	0.200	80.00	0.400
S2	0.250	60.00	0.350
S3	0.200	46.36	0.400
S4	0.150	60.00	0.350
S5	0.200	80.00	0.400
S6	0.150	100.00	0.350
S7	0.200	80.00	0.400
S8	0.150	100.00	0.450

S9	0.250	60.00	0.450
S10	0.284	80.00	0.400
S11	0.116	80.00	0.400
S12	0.250	100.00	0.450
S13	0.250	100.00	0.350
S14	0.200	113.64	0.400
S15	0.200	80.00	0.400
S16	0.200	80.00	0.400
S17	0.200	80.00	0.400
S18	0.200	80.00	0.484
S19	0.200	80.00	0.316
S20	0.150	60.00	0.450

2.4.3D Printing of Samples

After the material and production parameters were determined, a cube-shaped sample measuring 25x25x25 mm was generated in the Solidworks program in order to produce the test samples. It was saved in STL format and transferred to the Slic3r slicer program and with the help of this program, the Gcode file required for production was derived. The created production codes were transferred to our Creality Ender 3 Max model Cartesian Fused Deposition Modeling (FDM) 3D printer and production was carried out. Figure 1 shows a picture taken during production and the cross-sectional interior detail of the produced cube sample.

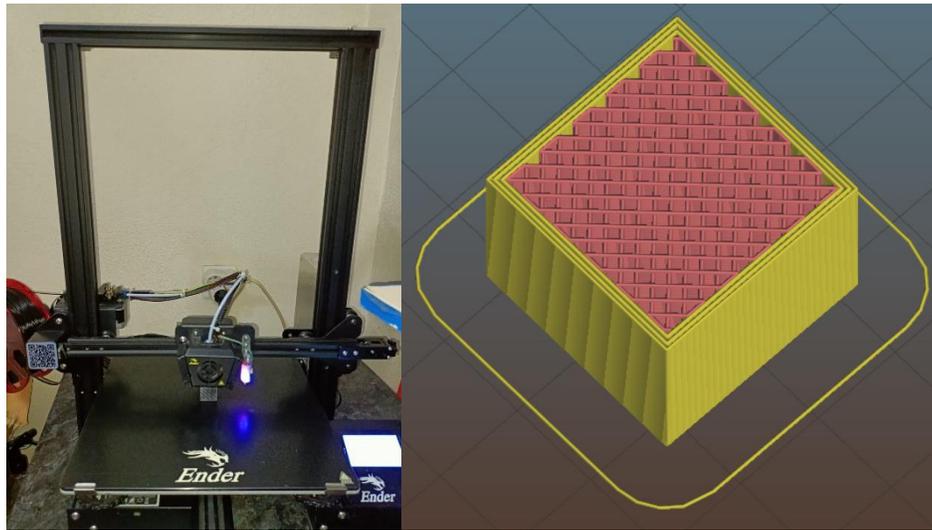


Figure 1: Sample production (left) and product interior section view (right)

2.5. Surface Roughness Measurements

After the production of a total of 20 samples according to the test order, the surface roughness values determined as a quality element must be determined. These measurements were made according to the production directions of the cube sample produced in accordance with 3D Cartesian production, and the axes, namely X, Y and Z, were determined. Then, surface roughness measurements were made three times in these directions and the average of them was taken. The surface roughness measuring device used is PCE brand RT-2000 model portable surface roughness device. Figure 2 shows a picture during surface roughness measurement and the directions of the axes determined in the sample.



Figure 2: Surface roughness measurement process (left) and determination of measurement axes (right)

2.6. Optimization Process

The process to be performed after the measurement results are obtained includes statistical analysis of the obtained data. The program chosen for statistical operations here is Minitab 20. The chosen optimization method is the RSM method. In this method, central composite design was preferred and a 2 level full factor experimental setup was established. Additionally, $\alpha=1.68179$ was used. The reason for choosing this method is that it obtains a large amount of information by using a small number of experiments according to parameter ranges and allows process optimization to be carried out in a shorter time. In addition, it is possible to make predictions with a small margin of error regarding the estimation of production parameters that should be selected for the best quality. Therefore, with the help of this method, surface roughness optimization was carried out separately for all three axes. In the final stage, the production parameters required for the best surface quality were optimized.

3. Results

3.1.1. Surface Roughness Measurements

The average of the Ra surface roughness measurement values taken from the samples produced first in this section is given in Table 4.

Table 4: Average surface roughness values measured according to axes

Sample Code	Averaged Surface Roughness Along X Axis (Ra) (μm)	Averaged Surface Roughness Along Y Axis (Ra) (μm)	Averaged Surface Roughness Along Z Axis (Ra) (μm)
S1	6.619	6.234	16.640
S2	6.189	5.594	19.490
S3	5.741	5.411	15.750
S4	2.511	2.194	16.670
S5	7.578	6.901	16.110
S6	3.158	2.486	16.210
S7	6.790	6.633	16.890

S8	3.977	4.315	15.320
S9	7.275	6.462	18.830
S10	7.182	7.492	22.760
S11	3.597	3.308	13.080
S12	4.288	4.015	19.650
S13	4.469	3.932	20.090
S14	5.818	5.843	15.200
S15	5.241	5.537	17.070
S16	6.348	6.573	17.260
S17	6.444	6.865	16.330
S18	6.581	6.058	17.670
S19	4.191	2.968	18.630
S20	4.830	4.529	17.890

When Table 4 is examined, it is seen that the lowest surface roughness values in the X and Y directions were obtained in the sample coded S4. The production parameters chosen here are 0.15 mm layer thickness, 60 mm/s printing speed and 0.35 mm extrusion width. As can be seen from here, as the levels of the parameters decrease, the surface quality increases. Additionally, the lowest surface roughness value in the Z direction was obtained in the sample coded S11. When the production parameters of this sample were examined, it was observed that the layer thickness value was selected as 0.116 mm. This result supports the previous interpretation. The decrease in the levels of production parameters has increased the surface quality, but this level decrease greatly increases the production time. For this reason, falling below the values selected in the study will increase the costs significantly.

3.1.2. Response Surface Regression Along X Axis

Regression and analysis of variance were carried out according to the surface measurement values on the X axis specified in the surface roughness measurements. In the statistical calculation, the standard deviation value was determined as 0.825811 and

the R^2 value was determined as 83.64%. Table 5 includes the variance analysis table and the coefficients in the calculations.

Table 5: Analysis of Variance Table for X axis Surface Measurements

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	34.8598	3.8733	5.68	0.006
Linear	3	20.3279	6.7760	9.94	0.002
Layer Thickness	1	13.8926	13.8926	20.37	0.001
Printing Speed	1	1.6755	1.6755	2.46	0.148
Extrusion Width	1	4.7598	4.7598	6.98	0.025
Square	3	10.4192	3.4731	5.09	0.021
Layer Thickness*Layer Thickness	1	4.8096	4.8096	7.05	0.024
Printing Speed*Printing Speed	1	2.7876	2.7876	4.09	0.071
Extrusion Width*Extrusion Width	1	4.8302	4.8302	7.08	0.024
2-Way Interaction	3	4.1127	1.3709	2.01	0.176
Layer Thickness*Printing Speed	1	2.5324	2.5324	3.71	0.083
Layer Thickness*Extrusion Width	1	0.6233	0.6233	0.91	0.362
Printing Speed*Extrusion Width	1	0.9570	0.9570	1.40	0.264
Error	10	6.8196	0.6820		
Lack-of-fit	5	3.9480	0.7896	1.37	0.368
Pure Error	5	2.8716	0.5743		
Total	19	41.6794			

As can be seen when the ANOVA table is examined, P-values are generally below 0.05. This indicates that the selected parameters and statistical calculations are regular. In Equation 1, the regression equation created to estimate the surface roughness value of variable parameters for the X axis is given.

$$\begin{aligned} \text{Surface Roughness Along X Axis} = & -83,2 + 202,3 \text{ Layer thickness} + 0,409 \text{ Printing speed} + 247,1 \\ & \text{Extrusion width} - 231,1 \text{ Layer thickness} * \text{Layer thickness} - \\ & 0,001100 \text{ Printing speed} * \text{Printing speed} - 231,6 \text{ Extrusion} \\ & \text{width} * \text{Extrusion width} - 0,563 \text{ Layer thickness} * \text{Printing speed} \\ & - 112 \text{ Layer thickness} * \text{Extrusion width} - 0,346 \text{ Printing} \\ & \text{speed} * \text{Extrusion width} \end{aligned} \quad (1)$$

Figure 3 shows the Pareto Chart analysis. Here, the effect of each parameter on the surface quality is observed, with effects above and below the reference calculated value.

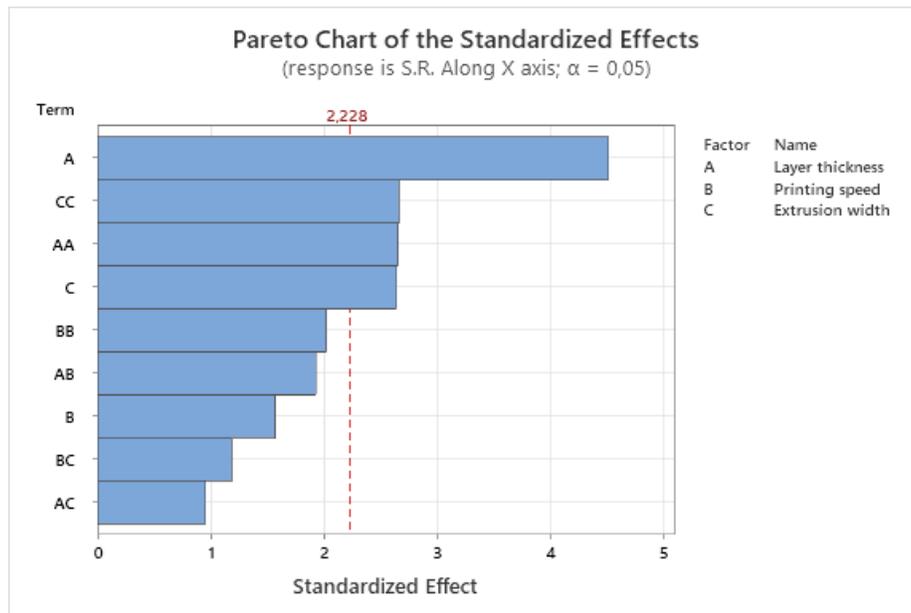


Figure 3: Pareto Chart Analysis of X axes

As seen in Figure 3, the most effective parameter on the surface roughness in the X axis is the layer thickness. Extrusion width * Extrusion width, layer thickness * layer thickness and extrusion width parameters largely affect the surface quality.

3.1.3. Response Surface Regression Along Y Axis

Regression and analysis of variance were carried out according to the surface measurement values on the Y axis specified in the surface roughness measurements. In the statistical calculation, the standard deviation value was determined as 0.785865 and the R² value was determined as 87.18%. Table 6 includes the variance analysis table and the coefficients in the calculations.

Table 6: Analysis of Variance Table for Y axis Surface Measurements

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	41.9941	4.6660	7.56	0.002
Linear	3	21.9614	7.3205	11.85	0.001
Layer Thickness	1	13.3758	13.3758	21.66	0.001
Printing Speed	1	0.7996	0.7996	1.29	0.282
Extrusion Width	1	7.7860	7.7860	12.61	0.005
Square	3	16.3426	5.4475	8.82	0.004
Layer Thickness*Layer Thickness	1	4.6191	4.6191	7.48	0.021
Printing Speed*Printing Speed	1	3.4023	3.4023	5.51	0.041
Extrusion Width*Extrusion Width	1	11.1537	11.1537	18.06	0.002
2-Way Interaction	3	3.6901	1.2300	1.99	0.179
Layer Thickness*Printing Speed	1	2.1914	2.1914	3.55	0.089
Layer Thickness*Extrusion Width	1	1.2904	1.2904	2.09	0.179
Printing Speed*Extrusion Width	1	0.2083	0.2083	0.34	0.574
Error	10	6.1758	0.6176		
Lack-of-fit	5	4.8717	0.9743	3.74	0.087
Pure Error	5	1.3042	0.2608		
Total	19	48.1700			

As can be seen when the ANOVA table is examined, P-values are generally below 0.05. This indicates that the selected parameters and statistical calculations are regular. In Equation 2, the regression equation created to estimate the surface roughness value of variable parameters for the Y axis is given.

$$\begin{aligned} \text{Surface Roughness Along Y Axis} = & -102,1 + 216,5 \text{ Layer thickness} + 0,351 \text{ Printing speed} + \\ & 341,7 \text{ Extrusion width} - 226,5 \text{ Layer thickness*Layer} \\ & \text{thickness} - 0,001215 \text{ Printing speed*Printing speed} - 351,9 \\ & \text{Extrusion width*Extrusion width} - 0,523 \text{ Layer} \\ & \text{thickness*Printing speed} - 161 \text{ Layer thickness*Extrusion} \\ & \text{width} - 0,161 \text{ Printing speed*Extrusion width} \end{aligned} \quad (2)$$

Figure 4 shows the Pareto Chart analysis. Here, the effect of each parameter on the surface quality is observed, with effects above and below the reference calculated value.

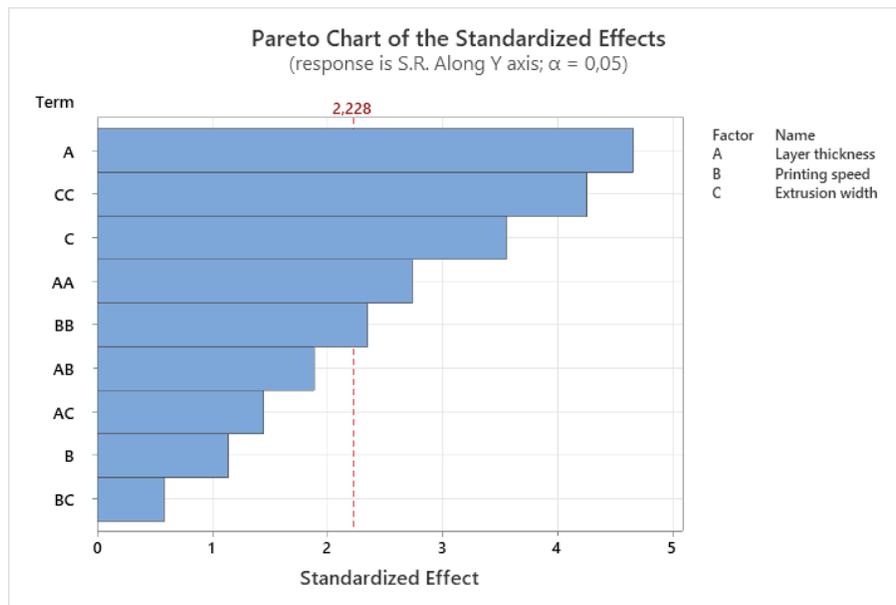


Figure 4: Pareto Chart Analysis of Y axes

As seen in Figure 4, the most effective parameters on the surface roughness in the Y axis is the layer thickness and Extrusion width * Extrusion width. Extrusion width, Layer thickness * layer thickness and printing speed * printing speed parameters largely affect the surface quality.

3.1.4. Response Surface Regression Along Z Axis

Regression and analysis of variance were carried out according to the surface measurement values on the Z axis specified in the surface roughness measurements. In the statistical calculation, the standard deviation value was determined as 1.00948 and the R² value was determined as 88.09%. Table 7 includes the variance analysis table and the coefficients in the calculations.

Table 7: Analysis of Variance Table for Z axis Surface Measurements

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	75.3414	8.3713	8.21	0.001
Linear	3	59.3226	19.7742	19.40	0.000
Layer Thickness	1	58.4358	58.4358	57.34	0.000
Printing Speed	1	0.4705	0.4705	0.46	0.512
Extrusion Width	1	0.4163	0.4163	0.41	0.537
Square	3	12.8414	4.2805	4.20	0.036
Layer Thickness*Layer Thickness	1	5.1214	5.1214	5.03	0.049
Printing Speed*Printing Speed	1	1.0374	1.0374	1.02	0.337
Extrusion Width*Extrusion Width	1	6.6139	6.6139	6.49	0.029
2-Way Interaction	3	3.1774	1.0591	1.04	0.417
Layer Thickness*Printing Speed	1	2.4753	2.4753	2.43	0.150
Layer Thickness*Extrusion Width	1	0.2556	0.2556	0.25	0.627
Printing Speed*Extrusion Width	1	0.4465	0.4465	0.44	0.523
Error	10	10.1906	1.0191		
Lack-of-fit	5	9.2171	1.8434	9.47	0.014
Pure Error	5	0.9735	0.1947		
Total	19	85.5320			

As can be seen when the ANOVA table is examined, P-values are generally below 0.05. This indicates that the selected parameters and statistical calculations are regular. In Equation 3, the regression equation created to estimate the surface roughness value of variable parameters for the Z axis is given.

$$\begin{aligned}
 \text{Surface Roughness Along Z Axis} = & 54,8 - 69,9 \text{ Layer thickness} + 0,081 \text{ Printing speed} - 187,1 \\
 & \text{Extrusion width} + 238 \text{ Layer thickness*Layer thickness} - \\
 & 0,000671 \text{ Printing speed*Printing speed} + 271 \text{ Extrusion} \\
 & \text{width*Extrusion width} + 0,556 \text{ Layer thickness*Printing} \\
 & \text{speed} - 71 \text{ Layer thickness*Extrusion width} - 0,236 \text{ Printing} \\
 & \text{speed*Extrusion width}
 \end{aligned} \quad (3)$$

Figure 5 shows the Pareto Chart analysis. Here, the effect of each parameter on the surface quality is observed, with effects above and below the reference calculated value.

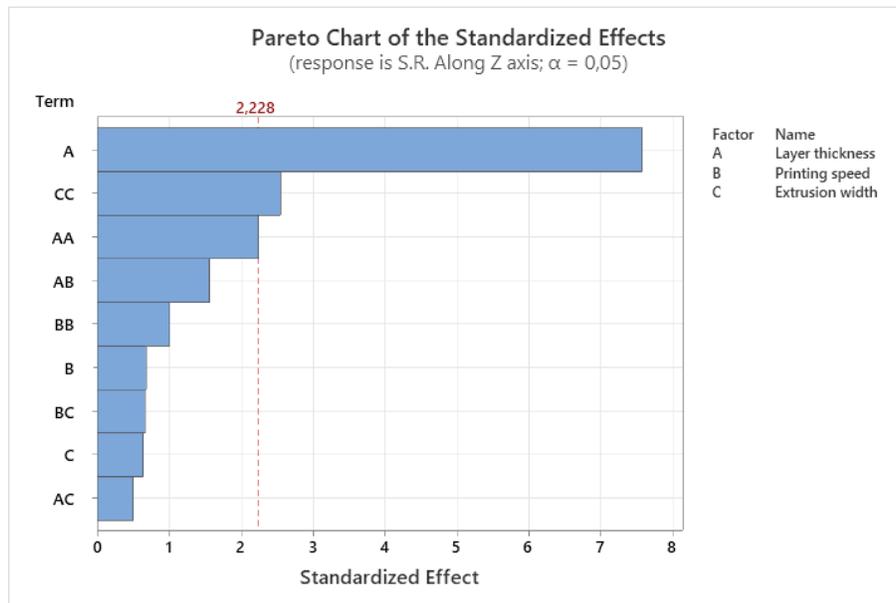


Figure 5: Pareto Chart Analysis of Z axes

As seen in Figure 5, the most effective parameter on the surface roughness in the Z axis is the layer thickness. Extrusion width * Extrusion width and layer thickness * layer thickness parameters largely affect the surface quality.

3.1.5. Response Optimization

After the statistical calculations, prediction calculations were made according to the variable levels of the selected printing parameters. Thus, according to the experimental and statistical calculation results, the values of the printing parameters that should be selected in order to obtain the lowest surface roughness value in all 3 directions were estimated. Figure 6 shows the graph showing the change in surface quality in each axis despite the parameters created for response optimization.

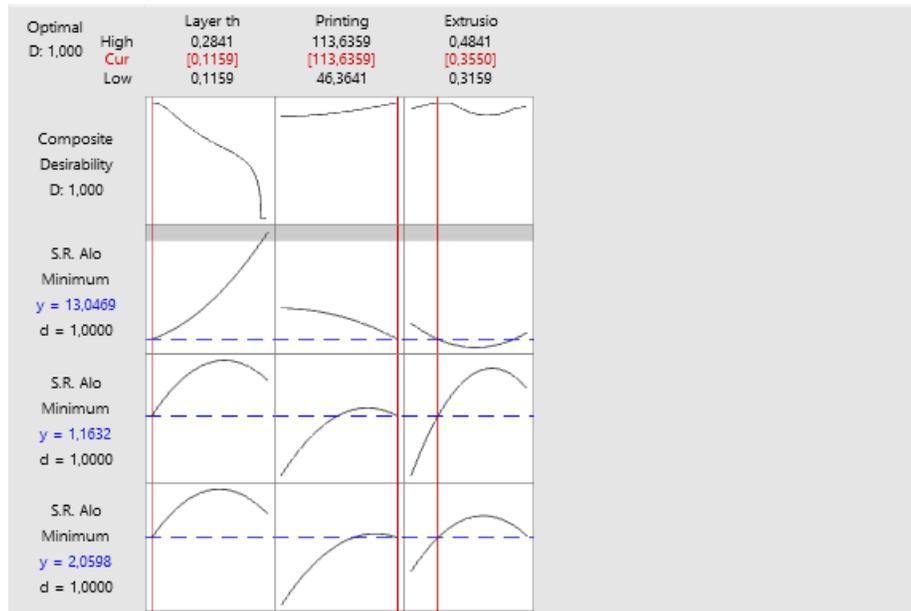


Figure 6: Response optimization plot.

As can be seen from the graph, it is necessary to select the printing speed as maximum and the minimum layer thickness for minimum surface roughness on each axis. Calculations specifically showed the extrusion width as 0.355 mm. When the levels of the parameters are selected in this way, surface roughness values of 13.0469 μm on the Z axis, 1.1632 μm on the Y axis and 2.0598 μm on the X axis can be obtained, respectively, as given in the graph.

4. Discussion and Conclusion

Due to the newness of the STH material, there are not many comparable publications and detailed experimental studies in the literature. In a study I found on surface quality, it was stated that surface roughness values between 1 and 7 μm can be measured according to measurements made on the X and Y axes [14]. Based on this, the surface roughness values and targeted parameter optimizations found in this study meet the reality.

In a recent study, they examined the effects of layer thickness, printing speed and filling method on the surface quality of PLA and ABS materials. Ra values were measured higher than approximately 4 μm [16]. As can be seen, it is possible to obtain better surface quality values with STH material than PLA and ABS materials.

The main contributions of the study can be listed below.

- Layer thickness directly affects the surface quality of the Z axis. In addition, it directly affected the measurements made in the X and Y axes on the upper surface. The main reason for this can be thought that as the height of the poured material increases, its distribution to the sides may become irregular.

- Although the effect of printing speed on surface quality seems to be less effective than other parameters in statistical calculations, it has significant effects on surface quality.
- Extrusion width, just like layer thickness, has a significant impact on material distribution because it changes the width of the material poured on the surface.
- According to the equations derived as a result of statistical calculations, the parameter estimates that will best provide the surface quality in each axis can be listed as follows; Layer thickness 0.1159 mm, printing speed 113.6359 mm/s and extrusion width 0.3550 mm are recommended. When production is made with these parameters, surface roughness values of 2.0598 mm in the X direction, 1.1632 mm in the Y direction and 13.0469 mm in the Z direction can be obtained.

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