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Research Article

Investigation on dimensional accuracy optimization of FDM printed UCFL bearing using response surface methodology

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Abstract

Additive manufacturing (AM) is a fabrication technology that enables flexibility in design and the manufacture of parts consisting of multiple materials. In this study, we focus on the dimensional accuracy optimization of the UCFL series roller bearing fabricated using the Fused Deposition Modeling (FDM). Printing parameters (layer thickness, infill density, and wall thickness) and their interactions were examined. The fabrication process was carried out by determining three levels for each parameter. Box-Behnken Design (BBD), which has three independent printing parameters at three levels, was used and fifteen pieces were produced using Akrilonitril Bütadien Stiren (ABS) material with a 3D printer. It has been determined that printing parameters affect the dimensional accuracy of the bearing, extrusion time and the amount of material consumed during the fabrication phase. ANOVA was performed to observe the effect of printing parameters on dimensional accuracy and extrusion time. Response Surface Methodology (RSM) analysis was used to optimize AM fabrication processes. Additionally, regression analysis was applied to mathematically model the dimensional accuracy values obtained as a result of experimental measurements. When the experimental results were examined, the best dimensional accuracy was determined as 35.9981mm using the combination of 150μm layer thickness, 50% infill density, and 1mm wall thickness.

Keywords: Additive manufacturing, dimensional accuracy, FDM, RSM, Box–Behnken Design

Introduction

Additive manufacturing (AM) is the process of producing a 3D object by adding materials, often layer by layer, to each other. The part designed in the computer environment is converted into the required format (*.STL) and divided into layers, and AM machines create and fuse these layers additively according to their own technique [1,2]. AM has primary usage purposes such as manufacturing complex geometries, reducing commissioning times, reducing fabrication investment costs, and being suitable for small-scale fabrication (custom fabrication) [3,4]. The application area of AM, also called 3D printing process or rapid prototyping, is increasing day by day. When additive manufacturing technology is examined, it is seen that parts and products produced in the fields of medicine, automotive, dentistry, architecture, personal equipment, jewellery and education are used [5,6].

There are many AM processes to produce industrial products of different shapes using metal, ceramic and plastic materials [7,8]. Some of these processes: Digital Light Processing (DLP)-liquid based, Fused Deposition Modeling (FDM)-solid based, and Direct Metal Laser Sintering (DMLS)-powder based. In this study, FDM, a material extrusion-based method, was used. Filaments wound on spools are pushed towards the nozzle through the spools in FDM. Just before the nozzle exit, it is melted through a heater and solidified layer by layer in the X-Y plane [9]. Mostly ABS, carbon fibre and PLA based filaments are used in FDM. Part printing speeds are low in FDM technology. However, the mechanical, chemical and thermal properties of the printed material are sufficient for many applications. It ranks first in non-industrial use due to its low costs. Polymer filaments can also be mixed with metal or ceramic powders to increase their strength properties [10].

The most important reason why FDM technology is limited in industrial applications is its disadvantages such as poor mechanical properties, repeatability and low accuracy [11,12]. High dimensional accuracy is expected as a result of the part produced in an AM process being reproduced under the same conditions. Printing parameters must be selected at the optimum level for this situation. Correct parameter selection results in quality process and product performance. Infill pattern, Build orientation, nozzle temperature, and infill density are some of the most common process parameters. Studies are carried out using different optimization methods to obtain the best surface quality and dimensional accuracy [13-16]. Radhwan at al. conducted studies to analyse the effect of the selected parameter on the quality surface quality of 3D printing objects and to find the optimum response of processing parameters using RSM [17]. The relations among responses and process parameters are determined and their validity is proven using ANOVA. Phadke et al. used Artificial Neural Networks (ANN) to establish a relationship between process and output parameters of the Laser Powder based fusion process for AlSi10Mg alloy [18]. Agarwal et al. studied the effect of wall thickness, filler density, printing platen temperature, printing speed, layer thickness and extrusion temperature on the dimensional accuracy of printed samples [19]. Alsoufi and Elsayed conducted a study on dimensional accuracy and surface roughness with a non-industrial, cost-effective desktop 3D printer [20]. In the study, samples with 100% filling, 40 mm in width and length, and 15 mm in height were manufactured using PLA, PLA+, ABS and ABS+ materials. As a result of the study, the best surface and dimensional quality was achieved with PLA+ material. Lieneke et al. achieved a study on the standard level with different additive manufacturing techniques [21]. In the study where FDM, selective laser sintering (SLS) and laser beam melting (LBM) techniques were examined, the dimensional accuracy and surface quality of the manufactured test samples were examined. It is designed to include a plate for measuring flatness, rectangularity, parallelism of test specimens, cylinders and holes for measuring roundness, cylindricity and concentricity. The manufactured test samples were measured with a coordinate measuring machine and optical measuring device.

In this study, a series of experimental studies were employed to examine the effects of different process parameters on dimensional accuracy and extrusion time during the fabrication of UCFL series roller bearings produced by FDM. We employed a full factorial design of the experiment with three factors: layer thickness, infill density, and wall thickness. The number of experiments was determined using the Box-Behnken Design (BBD), and the results were analysed using ANOVA. Response surface methodology (RSM) was applied to evaluate the impact of process parameters and their interactions on process output and to optimize the printing parameters.

Materials and Methods

Experiment apparatus

Dimensional accuracy of the final product obtained in FDM is very important in terms of cost and time savings. The biggest problem that arises with this technology is the low dimensional accuracy of the final product. FDM printers are generally devices that produce by pushing a filament material and flowing it through a nozzle kept at a certain temperature using injection logic. It is possible to print complex parts with this method. UCFL series roller bearing was designed in 3D on a computer using SolidWorks software in accordance with the specified criteria. All parts are produced from ABS material at room temperature. FDM-based Zaxe Z1 Plus 3D printer was used in the fabrication of roller. The 3D printer is capable of printing parts with maximum dimensions of 300x300x300 mm. Additionally, it has 50-400-micron layer resolution and 10-300 mm/s print speed capability. Under the same conditions, fifteen bearings were produced and dimensional accuracy measurements were started. Figure 1 shows the additive manufactured UCFL series roller bearing.

Figure 1. *UCFL series roller bearings fabricated by FDM*

Design of experiment

Response surface methodology (RSM) was employed to examine the relationship between printing parameters and output during the experimental design process. The calculations for the RSM were executed using the Minitab software. After the 3D printing experiments were conducted, three factors affecting accuracy in 3D printing were used in the experiments to understand the performance and the effect of the parameters on dimensional accuracy. The factors considered include layer thickness (A), infill density (B), and wall thickness (C), which are tested at 3 levels and designed using the Box-Behnken Design (BBD). The factors and levels used in the experimental design are given in Table 1.

Table 1. *Factors and levels utilized in RSM.*

Parameter	Notation	Unit	Level		
			-1	0	1
Layer Thickness	A	µm	150	200	300
Infill Density	B	%	30	50	70
Wall Thickness	C	mm	1	2	3

Box-Behnken Design (BBD) with three variables is acted at 3 levels (− 1, 0, and 1) (Table 1). Values of 150µm, 200µm, and 300µm were chosen for layer thickness. A value of 30%, 50%, and 70% was selected for infill density. Finally, values of 1mm, 2mm, and 3mm were selected for wall thickness. The experiments performed can be seen in Table 2.

Table 2. *The actual design factors and responses.*

Ex. No.	Input Variables			Responses	
	Layer Thickness	Infill Density	Wall Thickness	Roller Bearing Diameter (mm)	Extrusion Time (min)
1	150	30	2	36.7181	64.44
2	300	50	1	35.9098	33.52
3	150	50	1	35.9981	67.04
4	200	50	2	36.2081	51.44
5	200	70	1	35.4881	53.43
6	200	30	1	35.9192	45.08
7	200	50	2	36.2573	51.51
8	200	30	3	36.5791	50.30
9	300	70	2	36.2292	37.38
10	200	70	3	36.1482	55.49
11	150	50	3	36.6891	71.11
12	150	70	2	36.3125	74.02
13	200	50	2	36.1834	51.51
14	300	30	2	36.6181	32.51
15	300	50	3	36.5991	36.16

Results and Discussion

Evaluation of dimensional accuracy

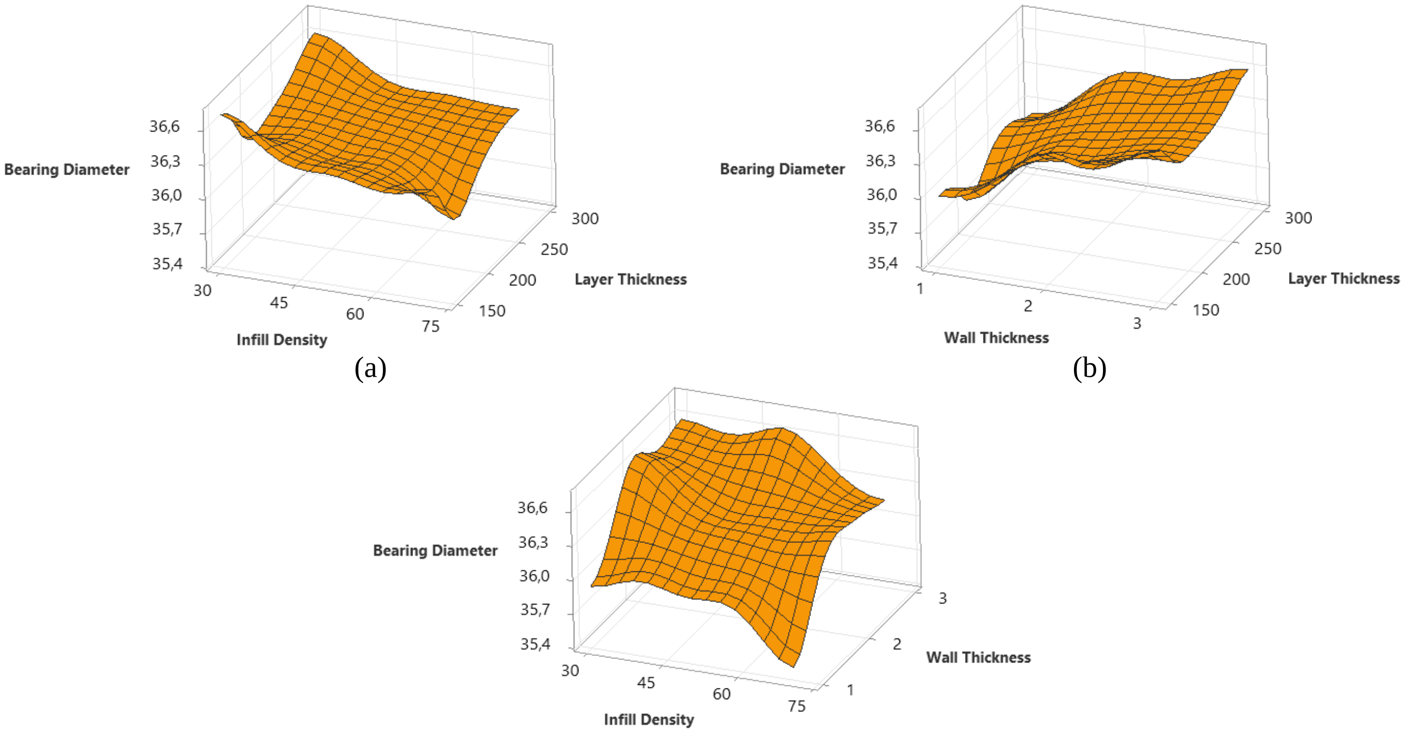
Analysis of variance (ANOVA) was applied to determine the individual interaction of layer thickness, infill density, and wall thickness printing parameters. ANOVA results of dimensional accuracy experiments performed using RSM are given in Table 3. F and P tests are very decisive in ANOVA. It is based on the premise that the higher the F value and the lower the P value, the greater the impact of changing that process parameter on the performance characteristics. If the P value is less than 0.05, the process parameter term is significant. In this case, all printing parameters are significant on the result. The "Lack of Fit F-value" of 0.13 implies the Lack of Fit is not important for relative to the pure error.

The percentage impact rates of layer thickness, infill density, and wall thickness factors on dimensional accuracy were found to be 16.18%, 20.99% and 62.80%, respectively. The results obtained prove the reliability of the analysis. As a result, the factor that had the highest impact on dimensional accuracy was wall thickness with a contribution rate of 62.80%. The layer thickness is the least significant variable as its percentage of contribution is only 16.18% and plays a minor role in the printing process for dimensional accuracy. The R^2 showed 99.97% which is close to 100%, while the rest of 0.03% was affected by other variables besides the predetermined control factor.

Table 3. *ANOVA results for dimensional accuracy.*

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
Layer Thickness	2	0.26459	0.132293	269.42	0.000	16.18
Infill Density	2	0.34314	0.171568	349.40	0.000	20.99
Wall Thickness	2	1.02652	0.513260	1045.26	0.000	62.80
Error	8	0.00393	0.000491			
Lack-of-Fit	6	0.00110	0.000183	0.13	0.978	0.030
Pure Error	2	0.00283	0.001415			
Total	14	1.66689				
R-sq = 99.97%				R-sq (adj) = 99.68%		

It has been observed with experimental results that the dimensional accuracy value can be controlled by the printing factors layer thickness, infill density, and wall thickness (Figure 2). According to the results obtained, it is understood that the wall thickness parameter is very important on dimensional accuracy. Figure 2 gives 3-D surface graphs that show the relationship between roller bearing diameter and process variables. The bearing bore diameter increases as the wall thickness increases as seen in Figure 2 (b) and (c). Dimensional accuracy is high in regions where the wall thickness value is 1mm. The highest dimensional accuracy occurred at low wall thickness and layer thickness values, as seen in Figure 2 (b). Infill density affected the bearing diameter inversely. Increasing density decreased the hole diameter. The diameter of the roller was high at low infill density values as seen in Figure 2 (a). The optimum fill rate should be 50% for high accuracy. Among the printing parameters, the layer thickness parameter has a very low effect on dimensional accuracy. The best dimensional accuracy was determined as 35.9981mm using the combination of 150µm layer thickness, 50% infill density, and 1 mm wall thickness.



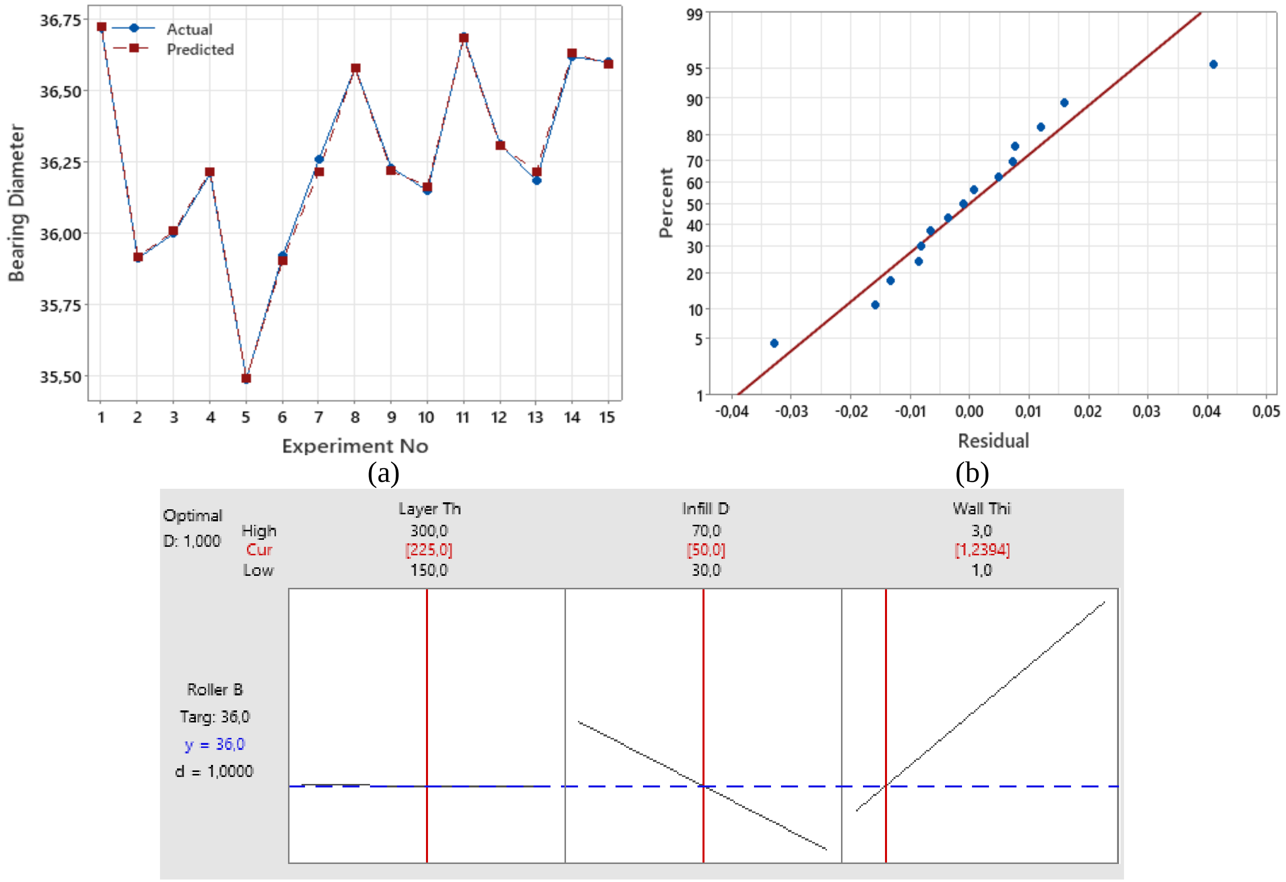
(a)

(b)

(c)

Figure 2. *Dimensional accuracy as the function of layer thickness, infill density and wall thickness.*

Regression analysis was applied to numerically express the connection between printing parameters and roller bearing diameter. With the equation obtained as a result of the analysis, diameter can be estimated depending on the parameters. Actual and predicted diameter values are shown graphically in Figure 3 (a). The difference between actual and estimated values for roller bearing diameter is quite low. In addition to the prediction model, the residual analysis in Figure 3 (b) was calculated to examine the adequacy of the model. If the residuals plot roughly along a straight line, then the normality assumption is satisfied. A check on the normal probability plot and linear residuals showed that the residuals were quite close to a straight line (Figure 3 (b)). Finally, optimization analysis was performed for dimensional accuracy. The target of the output parameter was determined as 36mm. The printing parameters required to achieve this goal were calculated as seen in Figure 3 (c). For the target value, layer thickness, infill density and wall thickness were calculated as 225µm, 50% and 1.2394mm, respectively.



(a) (b)

(c)

Figure 3. *(a) Timescale graph for roller bearing diameter (actual) and roller bearing diameter (predicted) (b) Normal probability plot of the residuals (c) Optimal parameters for roller bearing diameter from RSM optimization.*

Evaluation of extrusion time

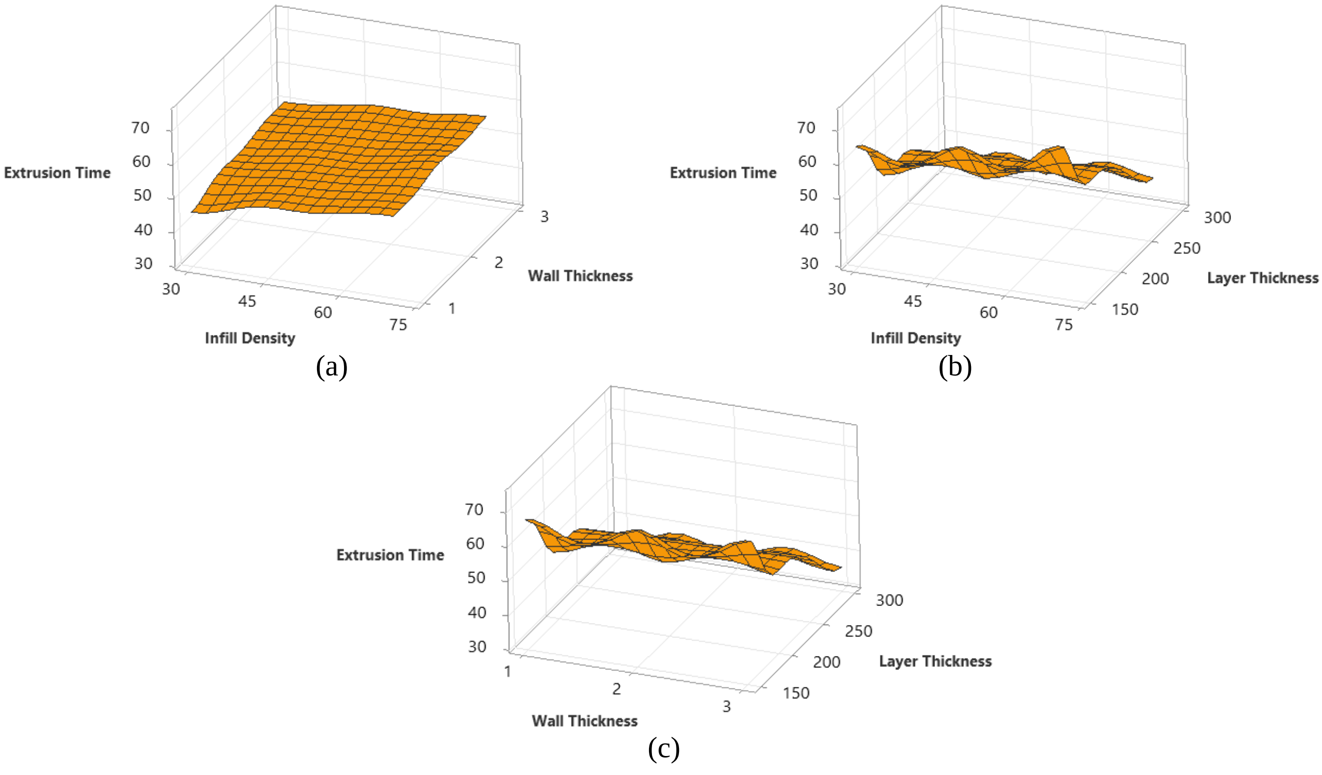
ANOVA was conducted as shown in Table 4 to see the effect of printing parameters on the extrusion time. The obtained F-value shows that the model is significant. Layer thickness, infill density, and wall thickness factors were found to be significant as their P values were less than 0.05. The “Lack of Fit F-value” of 10.66 implies the Lack of Fit is not important for relative to the pure error.

The percentage impact rates of layer thickness, infill density, and wall thickness factors on extrusion time were found to be 90.97%, 6.32% and 1.80%, respectively. The results obtained prove the reliability of the analysis. As a result, the factor that had the highest impact on dimensional accuracy was layer thickness with a contribution rate of 90.97%. The wall thickness is the least significant variable as its percentage of contribution is only 1.80% and plays a minor role in the printing process for dimensional accuracy. The R^2 showed 99.09% which is close to 100%, while the rest of 0.91% was affected by other variables besides the predetermined control factor.

Table 4. *ANOVA results for extrusion time.*

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
Layer Thickness	2	2349.53	1174.76	1079.96	0.000	90.97
Infill Density	2	98.00	49.00	75.05	0.000	6.32
Wall Thickness	2	24.74	12.37	2137	0.005	1.80
Error	8	1.70	1.09			
Lack-of-Fit	6	1.70	1.45	10.66	0.080	0.91
Pure Error	2	0.00	0,00			
Total	14	2475.67				
R-sq = 99.09%				R-sq (adj) = 98.78%		

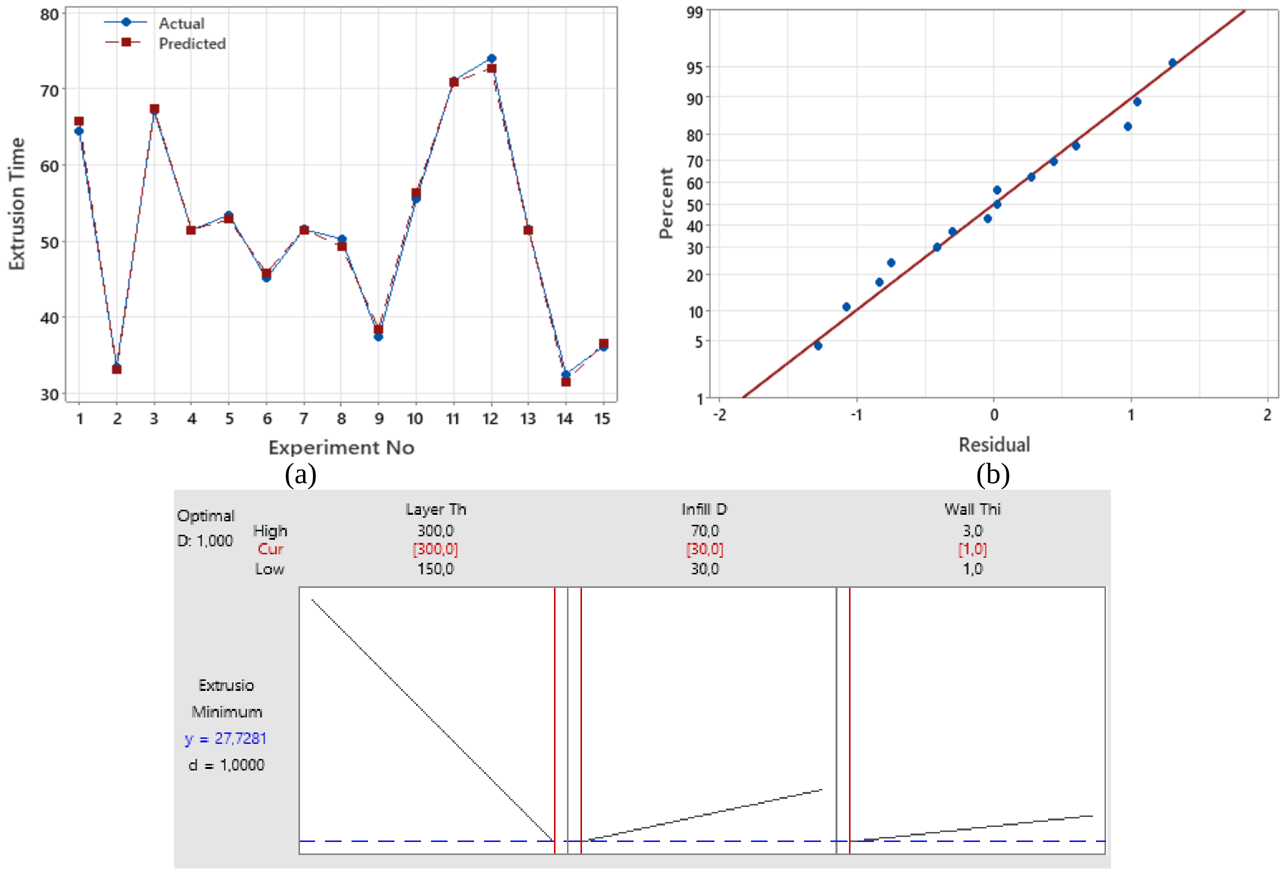
It has been observed with experimental results that the extrusion time value can be controlled by the pressure factors layer thickness, infill density, and wall thickness (Figure 4). When the effect of control factors on extrusion time is evaluated, it is understood that the layer thickness parameter is very important on the extrusion time. Figure 4 shows 3-D surface graphs that show the relationship between extrusion time and process variables. As seen in Figure 4 (b) and (c), extrusion time increases significantly with decreasing layer thickness. Other parameters have little effect on the result. The highest extrusion time was calculated as 74.02 minutes at 150μm, while the lowest extrusion time was calculated as 32.51 minutes at 300μm. In the parameters in Figure 4 (a), the effect of infill density is higher. As the filling rate increases, there is a linear increase in extrusion time. Among the printing parameters, the effect of the wall thickness parameter on extrusion time is quite low. The shortest extrusion time was determined as 32.51 minutes using the combination of 300μm layer thickness, 30% infill density, and 2mm wall thickness.



(a) (b) (c)

Figure 4. *Extrusion time as the function of layer thickness, infill density and wall thickness.*

Regression analysis was also applied to reveal the connection between printing parameters and extrusion time. The connection between the parameters and extrusion time was calculated and estimated. Actual and predicted extrusion time values are shown graphically in Figure 5 (a). Figure 5 (a) shows that the plotted points are mostly close to the fitted line, so the generated model can be considered a good approximation in estimating the predicted extrusion time values. In addition to the prediction model, the residual analysis in Figure 5 (b) was calculated to examine the adequacy of the model. A check on the normal probability plot and linear residuals showed that the residuals were quite close to a straight line (Figure 5 (b)). These values imply that the errors are normally distributed and support that the terms mentioned in the model are important. Finally, optimization analysis for extrusion was performed. The target of the output parameter is determined as the minimum value for this purpose. The printing parameters required to achieve this goal were calculated as seen in Figure 5 (c). Layer thickness, infill density and wall thickness were calculated as 300µm, 30% and 1mm, respectively for the target value.



(a) (b)

(c)

Figure 5. *(a) Timescale graph for extrusion time (actual) and extrusion time (predicted) (b) Normal probability plot of the residuals (c) RSM optimization.*

Conclusion

In this study, the dimensional accuracy and extrusion time of the UCFL series roller bearing produced using different printing parameters with FDM, one of the additive manufacturing methods, were examined. The experimental plan was determined using BBD, one of the RSM methods, and the results were analysed employing ANOVA. Three factors were preferred in the experimental design: layer thickness, filling density and wall thickness. Finally, RSM was applied to evaluate the interaction between printing parameters and output and to optimize the process parameters. Experimental studies showed that the wall thickness parameter had a significant effect on dimensional accuracy. It has been determined that the most important factor affecting the extrusion time output parameter is layer thickness. The best dimensional accuracy was determined as 35.9981mm using the combination of 150µm layer thickness, 50% infill density, and 1 mm wall thickness. The extrusion time in this experiment was calculated as 67.04 minutes.

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