Düzce University
Journal of Science & Technology

Research Article

Surface Texture Characterization and Parameter Optimization of Fused Deposition Modelling Process

Binnur SAĞBAŞ [a,*]

[a] *Department of Mechanical Engineering, Faculty of Mechanical Engineering,Yildiz Technical University, Istanbul, TURKEY*
* *Corresponding author's e-mail address: bsagbas@gmail.com*

ABSTRACT

Additive manufacturing (AM) is an emerging technology which provides opportunity to produce complex geometries layer-by-layer. Fused Deposition Modeling (FDM) is one of the additive manufacturing (AM) methods, widely used for manufacturing prototypes, models and functional thermoplastic parts as final product. Although FDM technology provides opportunity for manufacturing complex geometries, surface quality of the products cannot reach the required value yet. For this reason post processing operations which are time consuming and over costing, are applied to the finished parts. Alternatively, optimization of the FDM process parameters is another solution which is more economical way for improving surface quality of the printed parts.

The aim of the study is to optimize the FDM process parameters such as shell number, infill percentage, infill geometry and layer thickness, for improving surface quality of the Polylactic Acid (PLA) parts. L9 (3^4) standard Taguchi experimental design is applied for manufacturing of the samples. The manufactured surfaces are inspected by mechanical profilometer for obtaining 2D surface profiles. For determination of the deviation from desired value, signal-to-noise ratios were calculated as a quality characteristic by transforming the results for Ra and Rq surface roughness parameters. Analysis of variance (ANOVA) was used for determining significance of the testing parameters.

Keywords: *Fused deposition modeling (FDM), 3D printing, surface roughness, parameter optimization, experimental design*

Received: 10/05/2018, Revised: 04/06/2018, Accepted: 04/06/2018
* This study was presented at the The Third International Congress on 3D Printing (Additive Manufacturing) Technologies and Digital Industry (3D-PTC2018) and the abstract was printed in Abstract Book.

Eriyik Yığma Modelleme Sürecinin Yüzey Doku Karakterizasyonu ve Parametre Optimizasyonu

ÖZET

Eriyik Yığma Modelleme (EYM), prototip ve model imalatının yanında son ürün olarak kullanılabilecek nitelikte fonksiyonel termoplastik parçaların da imalatında yaygın olarak kullanılan bir eklemeli imalat yöntemidir. EYM teknolojisi her ne kadar karmaşık parçaların imalatına imkan sağlıyor olsa da, elde edilen ürünlerin yüzey kalitesi henüz istenilen seviyeye ulaşamamıştır. Bu nedenle istenilen yüzey kalitesini elde etmek için ürün yüzeyine son bitirme işlemleri uygulanmaktadır. Bu işlemler zaman alıcıdır ve ilave maliyete neden olmaktadır. Alternatif olarak, ürünlerin yüzey kalitesinin arttırılması için EYM işleminin parametrelerinin optimize edilmesi daha ekonomik bir çözümdür.

Bu çalışmanın amacı, EYM prosesi ile polilaktik asit (PLA) parça imalatında kabuk sayısı, dolgu oranı, dolgu geometrisi ve katman kalınlığı gibi parametrelerin yüzey pürüzlülüğü üzerinde etkisinin incelenerek, optimum parametrelerin belirlenmesidir. Numuneler Taguchi'nin standart L9 (3^4) deneysel tasarım seti kullanılarak imal edilmiştir. Numunelerin yüzeyleri mekanik profilometre ile ölçülerek, 2 boyutlu yüzey profilleri elde edilmiş ve sonuçlar sinyal/gürültü oranı kalite karakteristiğine dönüştürülerek, sonuçlardaki sapmalar belirlenmiştir. İşlem parametrelerinin anlamlılığını belirlemek için de son olarak Varyans analizi (ANOVA) uygulanmıştır.

Anahtar Kelimeler: *Eriyik Yığma Modelleme (EYM), 3B baskı, yüzey pürüzlülüğü, parametre optimizasyonu, deneysel tasarım*

I. INTRODUCTION

Fused Deposition Modeling (FDM) is an extrusion based additive manufacturing (AM) method which builds up the 3D geometries layer-by-layer by depositing of thermoplastic polymers according to 3D CAD model of the part. The deposition of the semi-molten thermoplastic material is applied by a temperature-controlled extrusion head (1-3). FDM technology provides opportunity for manufacturing complex geometries with easy support removal, minimum material consumption and simple application procedure. The technology has widely been used for prototype and mold manufacturing in aerospace, automotive and biomedical area. Rarely it is used for manufacturing final products because dimensional accuracy and surface quality of FDM manufactured parts are still questionable. By development of the process it is aimed to build up functional parts as final products (4-6).

Many researches have been performed for development of surface quality of final product by finishing operations and FDM process parameter optimization. Because the finishing operations are time consuming and cause additional cost, parameter optimization is more suitable way for obtaining better surface quality (6). In literature studies it has been reported that layer thickness is the most effective FDM parameter on surface quality of the product. Besides, part orientation, road width, deposition speed and extruder temperatures are the parameters affect the surface roughness of FDM parts (7-9). In ref. (10) authors proposed a model to analyze the effect of cross-sectional shape, layer thickness, overlap between adjacent layers and surface angle on surface quality of the product. Martínez et al.(11) applied Taguchi experimental design and ANOVA analysis for selecting the best process parameters for surface quality of FDM manufactured parts. In ref.(12) Taguchi experimental design and ANOVA used for determination effect of FDM process parameters such as table temperature, nozzle temperature, printing speed, fill percentage, layer thickness, on surface roughness of the product. Studies have been going on rapidly for development FDM process to obtain final product with high surface quality and dimensional accuracy.

In this study it is aimed to define optimal FDM parameters for improving surface quality of PLA product. Taguchi experimental design and ANOVA analysis were applied for the parameters such as; shell number, infill percentage, infill geometry and layer thickness.

II. Materials and Methods

In this study, poly lactic acid (PLA) filament, the most commonly used feed stock in FDM processes, was used as sample material. Diameter and thickness of the samples were 30 mm and 4 mm respectively. FDM technique was used for manufacturing samples. Technical properties of the FDM machine are given in Table 1.

Table 1. *Technical properties of the FDM machine.*

Specification	Value
Printing Volume	200mm x 200 mm x 200 mm
Resolution / Detail	80 micron – 300 micron
Position Precision	XY 11 micron (0.011 mm), Z 2.5 micron (0.0025 mm)
Printer Size	451 mm x 471 mm x 418 mm
Software	Matter Control
File Formats	STL,OBJ,AMF
Raw Materials	PLA and ABS

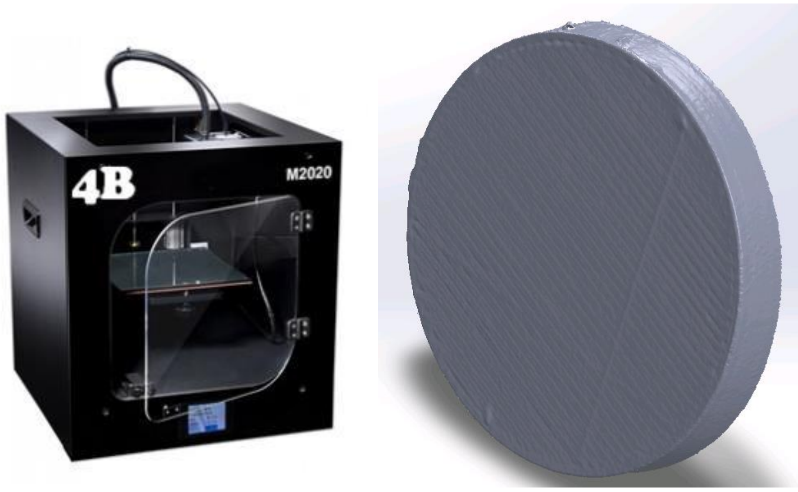


Figure 1. *(a) FDM machine used to product the samples, (b) PLA sample.*

For improving surface quality, it is important to define effect of process parameters on the properties of final product. Four different process parameters such as shell number, infill percentage, infill geometry and layer thickness have been chosen for this study with three level of each parameter. To determine the effect of each process parameters and their levels on surface quality of the FDM manufactured parts, lots of experiments should be done which is time consuming, not practical and not economical. Therefore, to decrease the number of required experiments, a standard Taguchi experimental plan (L9) was chosen. In order to determine the deviation from desired value, signal-to-noise ratios were calculated as a quality characteristic by transforming the results for Ra and Rq surface roughness parameters. The-lower-the-better, the-higher-the-better and the-nominal-the–better are the quality characteristics that can be used for the analysis of S/N ratio (13). In this study the-lower-the-better quality characteristic was chosen for determining the surface roughness of FDM manufactured PLA samples.

There are many parameters which affect quality of the part manufactured by FDM method. In this study four of these parameters such as shell number, infill percentage, infill geometry, and layer thickness were chosen. Three different levels for each parameter were used for manufacturing test samples. Factors and their levels can be seen in table 2 below.

Table 2. *Control factors and their levels.*

Level	**Factors**			
	Shell number	**Infill percentage (%)**	**Infill geometry**	**Layer thickness (mm)**
1	2	5	Honeycomb	0,15
2	3	25	Triangular	0,25
3	4	50	Rectangular	0,35
Factor code	A	B	C	D

In order to determine significance of the testing parameters and calculate the contribution of each parameter to the results, analysis of variance (ANOVA) was used. The confidence level of the analysis was the $\alpha=0.05$. Taguchi L9 experimental plan can be seen in table 3.

Table 3. *Taguchi L9 experimental layout.*

Exp. No	**Shell number**	**Infill percentage %**	**Infill geometry**	**Layer thickness (mm)**
1	2	5	Honeycomb	0.15
2	2	25	Triangular	0.25
3	2	50	Rectangular	0.35
4	3	5	Triangular	0.35
5	3	25	Rectangular	0.15
6	3	50	Honeycomb	0.25
7	4	5	Rectangular	0.25
8	4	25	Honeycomb	0.35
9	4	50	Triangular	0.15

Surface roughness measurements were taken with Veeco Dektak XT Bruker mechanical stylus profilometer on the top surface of the samples. Tip radius of the stylus instrument was 5 µm while sampling length was 2.5 mm, cut off was 2.5 mm and traverse length was 12.5 mm. At least three repeated surface roughness measurement were taken from the different region of the surface. The mean value of these measurements was used in analysis.

III. RESULTS AND DISCUSSION

There are lots of surface roughness parameters which are used for evaluating surface quality and functionality. The most common surface roughness parameter is arithmetic mean roughness Ra and it can be measured simply by any of the surface roughness measurement device. Another mostly used roughness parameter is Rq which is generally bigger than Ra value. Defining Ra from measured profile is easier than Rq. The Ra parameter represents the arithmetic mean of the absolute vertical deviation values, z(x), within the sampling length, l. While the Rq is the root mean square value of those z(x) values, within the same sampling length and characterize optical property of the surface. Formulas for calculating Ra and Rq can be seen in equation 1 and 2 (14).

$$Ra = \frac{1}{l}\int_0^l |z(x)|\,dx \tag{1}$$

$$Rq = \sqrt{\frac{1}{l}\int_0^l |z^2(x)|\,dx} \tag{2}$$

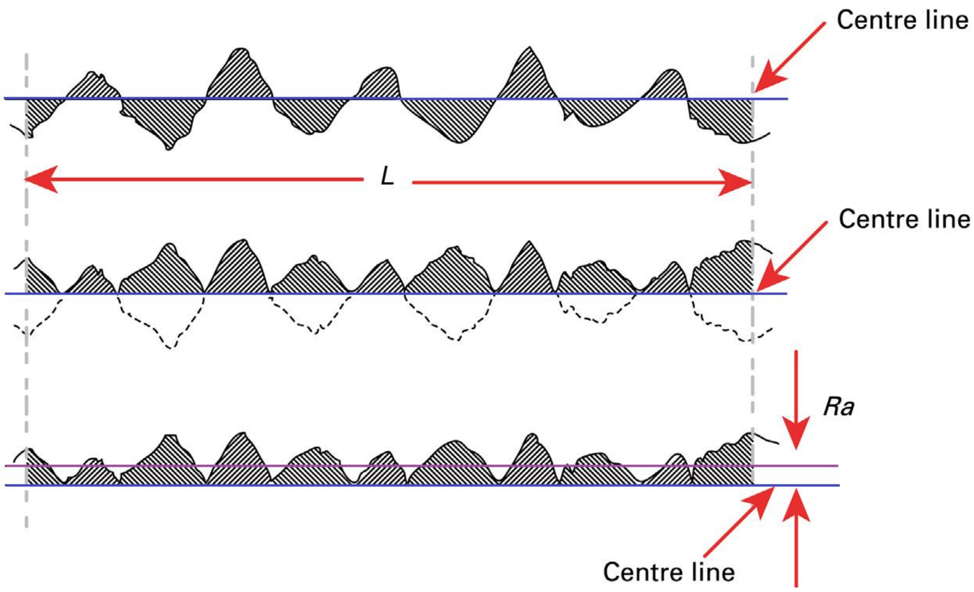


Figure 2. *Graphical deviation of Ra (14)*

Surface roughness measurement results and the signal-to-noise ratios were reported in table 4 with Taguchi's experimental layout. Mean value of three roughness measurement results can be seen in this table.

__Table 4.__ Results and calculated S/N ratios with applied experimental layout.

Exp. no	Factor codes and levels				Ra (µm)	Rq (µm)	S/N- Ra (dB)	S/N-Rq (dB)
	A	B	C	D				
1	2	5	Honeycomb	0.15	10,80	14,22	-20,67	-36,58
2	2	25	Triangular	0.25	8,91	11,37	-18,99	-34,91
3	2	50	Rectangular	0.35	7,11	8,32	-17,04	-30,15
4	3	5	Triangular	0.35	7,73	9,07	-17,76	-30,51
5	3	25	Rectangular	0.15	6,42	7,93	-16,15	-30,14
6	3	50	Honeycomb	0.25	4,57	5,59	-13,19	-27,31
7	4	5	Rectangular	0.25	6,43	7,42	-16,16	-28,19
8	4	25	Honeycomb	0.35	9,65	11,96	-19,69	-33,58
9	4	50	Triangular	0.15	9,21	11,30	-19,28	-33,22

Graphical representation of surface roughness measurement results Ra and Rq for each experiment can be seen in figure 3. Rq values are bigger than Ra values as expected. The roughness parameter values have been changed by different parameter combination. For determination effect of each parameter, main effects plot for S/N ratios for surface roughness Ra and Rq have been obtained by Minitab 16. These plots can be seen in figure 4.

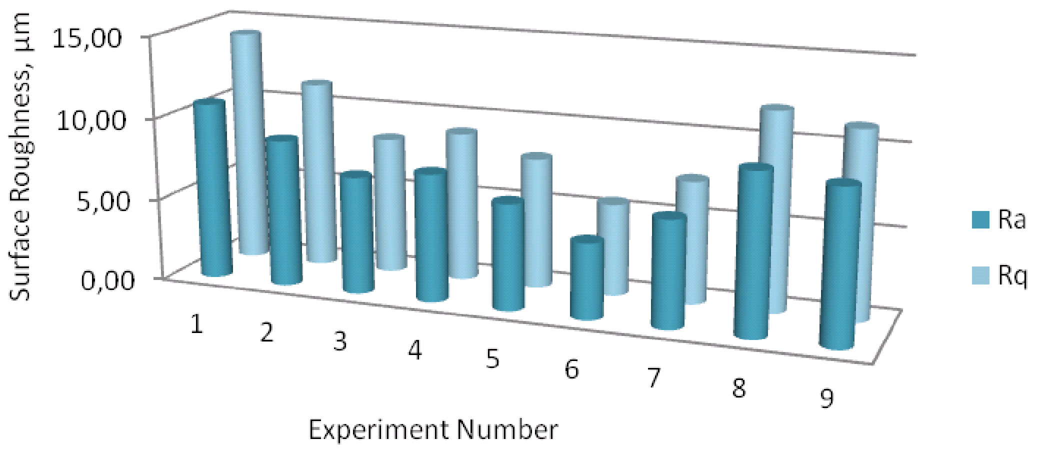
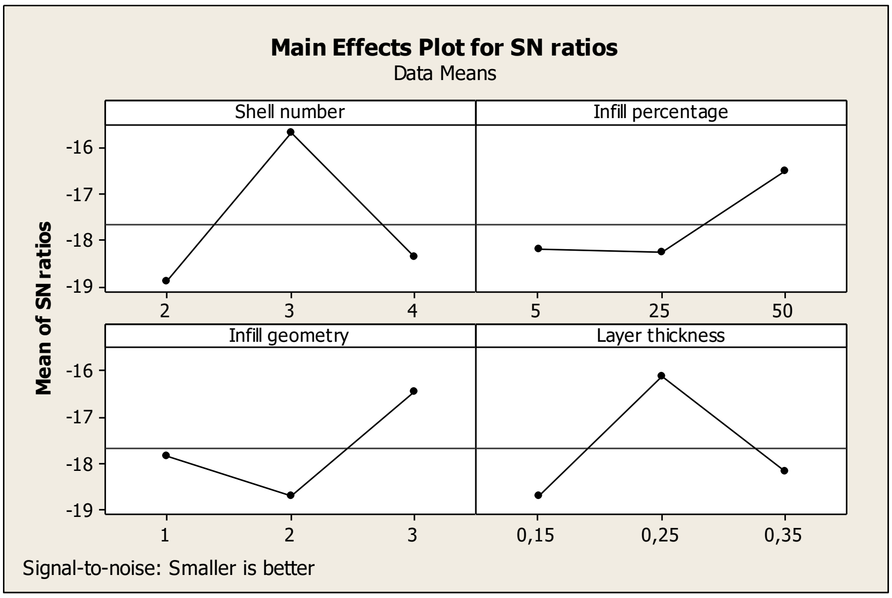
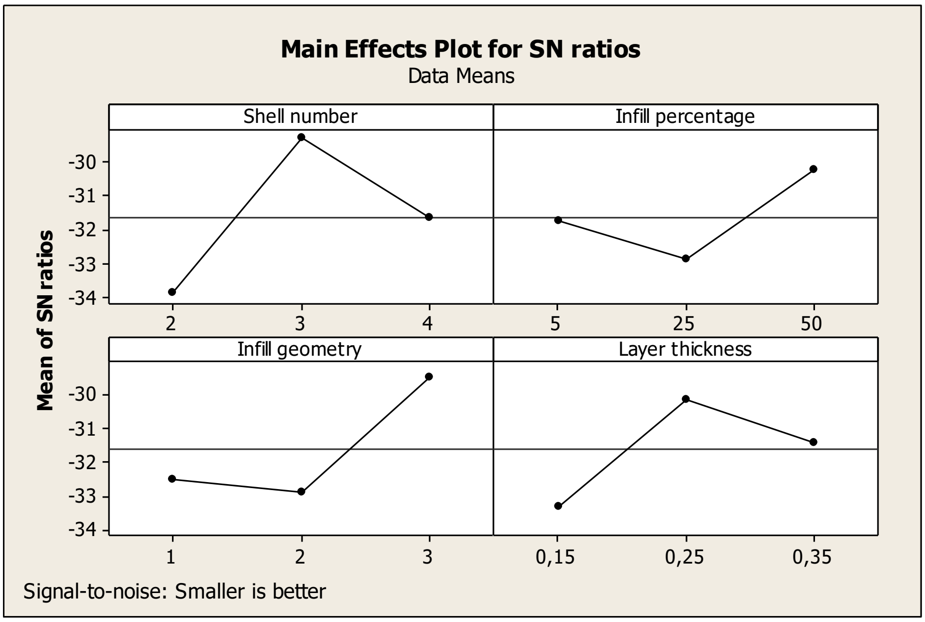


__Figure 3.__ The Ra and Rq parameter values for each experiment.

The optimal process parameters for minimum surface roughness value defined as A2B3C3D2 both for Ra and Rq. That means the minimum surface roughness obtained with 3 shell number, 50 % infill percentage, rectangular infill geometry and 0,25-layer thickness.



(a) *For the Ra parameter*



(b) *For the Rq parameter*

Figure 4 . *Main effects plot for S/N ratios both for surface roughness Ra* ***(a)*** *and Rq* ***(b)***

For determining statistical significance of parameters analysis of variance was applied. The results are reported in table 5. The degree of freedom for experiment factors was 2 and for error was 18. Therefore, table value of F was read as $F_{table\ 0,05\ (2,\ 18)}$ = 3.55. The calculated F values are higher than F_{table} that means all of the factors have significant effect on the surface roughness. According to the contribution ratios in table 4, the most effective parameter on surface quality is shell number with 40,51% contribution ratio, then layer thickness and infill geometry come with 24,70% and 22,49% contribution ratio respectively.

Table 5. Analysis of variance table.

Factors	Degree of freedom	Sum of squares (SS)	Variance (V)	F value	Contribution ratio (%)
Shell number	2	37,262	18,631	17965,75	40,51
Infill percentage	2	11,298	5,649	5447,33	12,28
Infill geometry	2	20,691	10,345	9975,83	22,49
Layer thickness	2	22,718	11,359	10953,20	24,70
Error	18	0,019	0,001		0,02
Total	26	91,987			100,00

Confirmation tests were applied for verifying the obtained parameter values, by using the optimal parameter values such as 3 shell number, 50 % infill percentage, rectangular infill geometry and 0,25 mm layer thickness. Surface roughness measurements were taken from five different region of the verification sample. Mean values of the recorded Ra and Rq parameters were 4,20 and 5,36 µm respectively, which are lower than the values recorded in Taguchi design. In consequence, the defined parameters could be considered as optimal parameters for surface roughness property of FDM manufactured surfaces.

IV. CONCLUSION

In this study, Taguchi experimental design was used for defining optimal parameters of FDM processes. Four different parameters such as " Shell number ", " Infill percentage ", " Infill geometry " and " Layer thickness " with three levels were applied in each experiment. It can be concluded that;

- Shell number is the most effective parameter on surface quality of the samples. Layer thickness, infill geometry and lastly infill percentage come respectively from high effective to low.
- The maximum Ra and Rq values for the selected Taguchi experiment lay out are; 10,80 and 14,22 µm respectively while the minimum values are 4,57 and 5,59 µm.
- Optimal parameter values were defined as 3 shell number, 50 % infill percentage, rectangular infill geometry and 0,25 mm layer thickness.
- In confirmation tests mean values of the Ra and Rq parameters were recorded as 4,20 and 5,36 µm respectively, which are lower than the values recorded in experimental design.
- In conclusion, it can be said that the defined parameters could be considered as optimal parameters for surface roughness property of FDM manufactured surfaces. Further experiments should be applied with different FDM machines. Also interaction of the parameters should be analyzed for making more reliable decisions.

ACKNOWLEDGEMENTS: The author would like to thank 4B Mühendislik for their support about PLA sample manufacturing by FDM method.

V. REFERENCES

[1] J. W. Tseng, C. Y. Liu, Y. K. Yen, J. Belkner, T. Bremicker, B. H. Liu, T. J. Sun and A. B. Wang, “Screw extrusion-based additive manufacturing of PEEK”, *Materials and Design*, vol. 140, pp. 209–221, 2018.

[2] A. Boschetto, V. Giordano and F. Veniali, "3D roughness profile model in fused deposition modelling," *Rapid Prototyping Journal*, vol. 19, no. 4, pp. 240-252, 2013.

[3] C.K. Chua, K.F. Leong and C.S. Lim, *Rapid prototyping: principles and applications*. 3rd ed. Singapore: World Scientific; 2010, ch.4, pp.137-145.

[4] D.S. Ingole, A.M. Kuthe, S.B. Thakare and A.S.Talankar, " Rapid prototyping–a technology transfer approach for development of rapid tooling" *Rapid Prototyping Journal*, vol.15, no.4, pp. 280-290, 2009.

[5] O.S. Ivanova, C. B. Williams and T.A. Campbell, “Additive manufacturing (AM) and nanotechnology: promises and challenges" Campbell, *Rapid Prototyping Journal*, vol.19, no.5, pp.353-364, 2013.

[6] R. Singh, S. Singh, I.P. Singh, F. Fabbrocino and F. Fraternali, "Investigation for surface finish improvement of FDM parts by vapor smoothing process", *Composites Part B*, vol. 111, pp. 228-234, 2017.

[7] R. Anitha, S. Arunachalam and P. Radhakrishnan, "Critical parameters influencing the quality of prototypes in fused deposition modelling", *Journal of Materials Processing Technology*, vol. 118 (1–3), pp. 385-388, 2001.

[8] S.O. Akande, "Dimensional Accuracy and Surface Finish Optimization of Fused Deposition Modelling Parts using Desirability Function Analysis", *International Journal of Engineering Research & Technology (IJERT)*, vol. 4, no. 04, 2015.

[9] B. Vasudevarao, D.P. Natarajan and M. Henderson, "Sensitivity of RP surface finish to process parameter variation", *Proceedings of solid free form fabrication*, Austin, USA. 2000, pp. 252-258.

[10] D.K. Ahn, H. Kim and S. Lee, "Surface roughness prediction using measured data and interpolation in layered manufacturing", *Journal of Material Process Technol*ogy, vol. 209, pp. 664–671, 2009.

[11] J. Martínez, J.L. Diéguez, A. Pereira and J.A. Pérez, "Modelization of surface roughness in FDM parts", *AIP Conference Proceedings*, 2012, vol.1431, pp. 849–1856.

[12] F. Kartal, "Taguchi Metodolojisi ile Eriyik Yığma Modelleme Süreci Parametrelerinin Optimizasyonu", *International Journal of 3D Printing Technologies and Digital Industry*, vol. 1, no.1, pp. 49-56, 2017.

[13] M. Sirvancı, *Kalite İçin Deney Tasarımı Taguci Yaklasımı*, Literatur Yayıncılık, Istanbul, 1997.

[14] R. Leach, *Fundamental Principles of Engineering Nanometrology*, Second edition, Elsevier Inc., 2014, pp.252-253.