Çukurova Üniversitesi Mühendislik Fakültesi Dergisi, 37(2), ss. 449-458, Haziran 2022
Cukurova University Journal of the Faculty of Engineering, 37(2), pp. 449-458, June 2022

An Investigation on Dimensional Accuracy of 3D Printed PLA, PET-G and ABS Samples with Different Layer Heights

Çağın BOLAT[*1] ORCID *0000-0002-4356-4696*
Berkay ERGENE[2] ORCID *0000-0001-6145-1970*

[1]*İstanbul Technical University, Faculty of Mechanical Engineering, Beyoğlu, İstanbul*
[2]*Pamukkale University, Faculty of Technology, Department of Mechanical Engineering, Denizli*

Geliş tarihi: 18.03.2022 *Kabul tarihi: 30.06.2022*

Atıf şekli/ How to cite: BOLAT, Ç., ERGENE, B., (2022). An Investigation on Dimensional Accuracy of 3D Printed PLA, PET-G and ABS Samples with Different Layer Heights. Çukurova Üniversitesi, Mühendislik Fakültesi Dergisi, 37(2), 449-458.

Abstract

In this study, the effect of filament type and layer height on the dimensional accuracy of the 3D printed tensile test samples from PLA, PET-G, and ABS was investigated in depth. Based on the fused filament fabrication (FFF) technology, tensile test samples were produced with various layer heights (0.2 mm, 0.3 mm, and 0.4 mm) while the other printing parameters were kept constant, except for nozzle and building platform temperature. Length, width, and height values of the produced test samples were measured, and obtained results were compared with design dimensions to observe the dimensional accuracy of each sample. Also, surface roughness measurements were performed on the samples to examine their final surface quality. From dimensional measurements, it was seen that the most accurate results were recorded for PET-G (in length and height) and PLA (in width) samples. Furthermore, the best surface quality was attained in PLA samples compared to other filaments.

Keywords: Dimensional accuracy, Fused filament fabrication, PLA, PET-G, ABS

Üç Boyutlu Baskı ile Farklı Katman Yüksekliklerinde Üretilmiş PLA, PET-G ve ABS Parçaların Boyutsal Doğruluğu Üzerine Bir Araştırma

Öz

Bu çalışmada, PLA, PET-G ve ABS'den 3D baskılı çekme testi numunelerinin boyutsal doğruluğuna filament tipi ve katman yüksekliğinin etkisi derinlemesine araştırılmıştır. Eriyik filament üretimi teknolojisine dayalı olarak, çeşitli katman yüksekliklerinde (0,2 mm, 0,3 mm ve 0,4 mm) çekme test numuneleri üretilirken, meme ve bina platform sıcaklığı dışındaki diğer parametreler sabit tutulmuştur. Üretilen test numunelerinin uzunluk, genişlik ve yükseklik değerleri ölçülerek, elde edilen sonuçlar tasarım boyutları ile karşılaştırılarak her bir numunenin boyutsal doğruluğu gözlemlenmiştir. Ayrıca, nihai yüzey kalitelerini incelemek için numuneler üzerinde yüzey pürüzlülük ölçümleri yapılmıştır.

[*]Sorumlu yazar (Corresponding author): Çağın BOLAT, *caginbolat@itu.edu.tr*

Boyutsal ölçümlerden en doğru sonuçların PET-G (uzunlukta ve yükseklikte) ve PLA (genişlikte) numuneleri için kaydedildiği görüldü. Ayrıca PLA numunelerinde diğer filamentlere kıyasla en iyi yüzey kalitesi elde edilmiştir.

Anahtar Kelimeler: Boyutsal doğruluk, Eriyik filament üretimi, PLA, PET-G, ABS

1. INTRODUCTION

In today's industrial world, although traditional manufacturing methods like machining, casting, welding, powder metallurgy, and plastic forming are more widespread for metallic [1,2], polymeric [3,4], composite [5-7], and ceramic [8] parts, this custom has begun to change in recent years. Three-dimensional (3D) printing technology is one of the modern production technologies that facilitates the manufacturing of complex-shaped objects [9,10]. Also, 3D printing technology has a number of advantages in comparison with other traditional production methods since it provides the production with shorter time and less material usage. Especially in the last decade, the general tendency on 3D printers for production of polymer materials has grown dramatically due to their low melting temperature, easy accessibility and low cost. It is a common idea that the fused filament fabrication (FFF) technique is the most widespread strategy to create a 3D printed product or prototype. At this point, when the manufacturing steps of a part printed with FFF is focused on, it can be noticed that there are three main steps; designing, slicing and main manufacturing. The FFF-based 3D printer produces the final-shaped part with deposition of layers from filament material by managing the heated nozzle on the compatible path with g-code [11]. Although not limited to only some thermoplastic materials, acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and polyethylene terephthalate glycol (PET-G) filaments are frequently used in 3D printers working with FFF principles.

It is known that dimensional accuracy and surface roughness have great importance for some engineering applications such as polymer heat exchanger, gear mechanism, implant or scaffolds which can be fabricated with FFF. From the literature efforts, it can be seen that FFF method is widely used for the production of investment casting molds [12,13]. Besides, it was reported that FFF offered 50% cost reduction and time saving when it was compared with traditional metal mold fabrication process [14]. According to Wohler report [15], tooling manufactured with FFF include thermoplastic fixtures, jigs, guides, press fixtures which are often required in small quantities on an assembly line. Especially topology- optimized parts in aerospace and automotive sectors are mostly preferred to be FFF method because of its advantages over traditional manufacturing methods such as time consuming and ease of production of complex parts.

When the literature efforts are examined, it is seen that the effect of FFF parameters on the mechanical behaviors were investigated with details [16,17]. However, only limited number of studies that focus on the influences of the FFF parameters on dimensional accuracy have been performed up to now by the researchers. In their study, Hanon et al. [18] focused on the influence of the print orientation, raster direction angle, filament color and layer height on dimensional accuracy of the dog-bone tensile test specimens. As a result of the study, they have expressed that FFF printers could create polymer parts with more than 98% of dimensional accuracy. In addition, layer height was found as one of the most decisive factors affecting the dimensional accuracy. On the other hand, it was emphasized by the same research team that the exact divisibility of the part height by the layer height also significantly affects the dimensional accuracy. Aside from this work, the effect of printing parameters on dimensional accuracy of FFF parts was also examined by Sood et al. [19]. In another study [20], dimensional accuracy analyses of the FFF parts were carried out with the help of grey relational grade analysis. According to obtained results, it was revealed that the best dimensional accuracy was obtained 3D printed part with layer height of 200 μm, raster direction of 0^o angle and build orientation of 0^o and 90^o. Mohamed et al. [21] considered the effect of FFF parameters on the surface roughness and dimensional accuracy of the 3D printed parts. Maurya et al. [22] conducted a study in which the authors tried to comprehend the effect of layer height, raster angle and orientation on dimensional accuracy of 3D printed PLA parts printed by FFF technology. As a result of their study, the investigation group asserted that the best process parameter condition was found as the lowest layer thickness (0.1 mm), raster angle and orientation of 0^o. Additionally, it was noted that the dimensions of the 3D printed parts were smaller than the CAD model because of the shrinkage during cooling of the material after the deposition of layer. Nidagundi et al. [23], Anusree et al. [24], and Wang et al. [25] reported that the smallest layer height was determined as the optimal layer height level for the best dimensional accuracy levels of 3D printed ABS parts according to Taguchi's experimental designs. Unlike, the optimal level of layer thickness was decided to be medium level (0.178 mm) in other studies [19,26]. Similar to efforts were conducted on FFF applied ABS parts, some performances [27,28] were also carried out about influences of FFF parameters on PLA parts as well. These efforts showed that any direct relation between the layer height and dimensional accuracy was not observed when the findings of these studies were compared. Lastly, Zharylkassyn et al. [29] claimed that the layer thickness levels between 0.1 mm and 0.2 mm is more likely to be optimal for the dimensional accuracy of FFF parts that uses ABS or PLA materials when the studies in literature reviewed in depth.

In this study, the effect of layer height on the dimensional accuracy of 3D printed tensile test samples prepared with three different materials (PLA, PET-G, and ABS) was investigated. To manufacture the polymer samples, FFF methodology was used. Using different polymer filaments, the effect of the base material on the dimensional accuracy was tested and evaluated. In addition, to analyze the product quality detailed roughness measurements were conducted on the sample surfaces.

2. MATERIALS AND METHOD

In this investigation, three different thermoplastic filaments were used. In this context, PLA, PET-G, and ABS filaments were selected due to their widespread usage in industrial and academic applications.

All filaments were supplied from Microzey Company (Istanbul, Turkey). According to the supplier information, Table 1 given below shows the principal features of these filament materials.

Table 1. Properties of polymer filaments

Property	**PLA**	**PET-G**	**ABS**
Colour	Black	Yellow	Grey
Diameter	1.75	1.75	1.75
Density (kg/m^3)	1240	1290	1040
Bed temperature	60-80	60-80	80- 120
Printing temperature (°C)	190-210	210-250	220-250
Elasticity modulus (MPa)	1500	2100	1250
Tensile strength (MPa)	50	46	48
Elongation at break (%)	7	8	5

PLA and PET-G samples were 3D printed by using Ender 3 Pro V2 model 3D printer (print size of 220x220x250 mm, maximum heated bed temperature of 110 ^{0} C, and maximum print speed of 180 mm/s). During the manufacturing, black and yellow colors were adopted for PLA and PET-G respectively.

Aside from PLA and PET-G samples, ABS samples were 3D printed with a Zaxe X2 model printer which offers a printing volume of 200mmx200mmx200mm. Also, its maximum building platform temperature and nozzle temperature can reach up to 110 ^{0} C and 280 ^{0} C respectively. In addition, usually, 0.4 mm nozzle diameter and filament with 1.75 mm is preferred mostly in this kind of printer. Besides, during the production of ABS samples, grey color was chosen. In Table 2, all manufacturing parameters can be glanced at in detail.

Table 2. FFF parameters selected for 3D printing

Parameter	**PLA**	**PET-G**	**ABS**
Layer height (mm)	0.2;0.3;0.4	0.2;0.3;0.4	0.2;0.3;0.4
Infill rate (%)	100	100	100
Infill type	Line	Line	Line
Build direction	Flat	Flat	Flat
Support structure	None	None	None
Adhesion type	None	None	None
Number of contours	3	3	3
Fan speed (%)	100	100	100
Raster angle (^{o})	45/-45	45/-45	45/-45
Printing speed (mm/s)	40	40	40
Nozzle temperature (^{o}C)	210	240	230
Building platform temperature (^{o}C)	60	70	80

For analyzing the dimensional accuracy of all of the filament types, the shape of well-defined tensile specimens was decided. According to the related standard of ASTM D638-14 Type IV, the determined printing design with height (thickness) of 3.4 mm can be seen in Figure 1. For this purpose, an assistant software and a slicing program (Ultimaker Cura 4.4.1) were utilized and they also can be seen with the used real-time printing machine in Figure 2 and Figure 3.

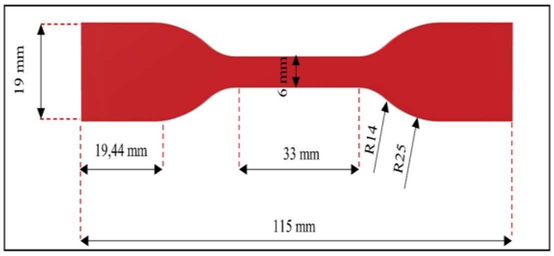

Figure 1. Design dimensions for tensile samples

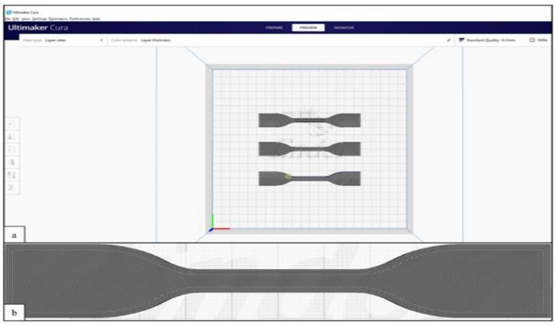
Figure 2. Slicing software for real-time building

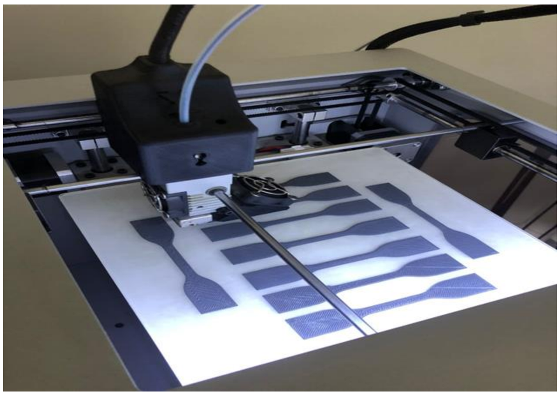
Figure 3. 3D printing machine and some of the produced tensile samples

3. RESULTS

3.1. Dimensional Accuracy Analyze Strategy

Figure 4 illustrates the measuring points of the 3D printed tensile specimens. Three different dimensions were taken as main control criteria: sample length (L_1, L_2 and L_3), gage width (W_1, W_2 and W_3), and height (H_1, H_2 and H_3). In addition, all measurement values obtained with digital caliper (Orion, 0.01 mm accuracy) were compared to the initial values of CAD design in order to ascertain the accuracy correctly. Table 3 indicates all measurement results for each product group. On the other side, standard deviation calculations were exhibited in related result graphs by error bars to show the precision (repeatability).

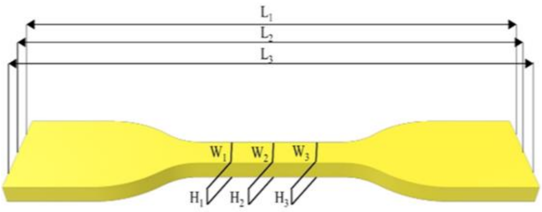

Figure 4. Measurement points on the samples

3.2. Accuracy in Length

A comparison graph can be found in Figure 5 for different polymers. It is noticed from Figure 5 that accuracy values are above 99% for all product types. If the filaments are checked up with each other, it is evident that accuracy values calculated for PET-G samples are higher than that of the others. Looking at Table 3 and Figure 5, it can be underlined that the highest average accuracy value of 99.99% belongs to the sample printed with PET-G although the lowest average accuracy value of 99.21% is detected for the sample prepared with ABS. This observation can be attributed to the high thermal expansion coefficient of ABS compared to other filament materials.

Table 3. The raw results obtained from dimensional measurements of tensile test samples

Material	Sample No	Layer height (mm)	Length measuring (mm)			Width measuring (mm)			Height measuring (mm)			Specimen weight (g)
			L_1	L_2	L_3	W_1	W_2	W_3	H_1	H_2	H_3	
PLA	1	0.2	114.52	114.56	114.58	6.18	6.20	6.20	3.33	3.31	3.32	5.8501
	2	0.2	114.60	114.62	114.61	6.25	6.26	6.29	3.28	3.28	3.31	5.8476
	3	0.2	114.57	114.58	114.55	6.17	6.19	6.21	3.33	3.30	3.33	5.8492
	4	0.3	114.86	114.84	114.88	6.22	6.20	6.22	3.21	3.19	3.20	5.4191
	5	0.3	114.73	114.75	114.88	6.16	6.13	6.12	3.20	3.14	3.22	5.4095
	6	0.3	114.60	114.68	114.77	6.20	6.17	6.15	3.13	3.14	3.20	5.3919
	7	0.4	114.71	114.82	114.69	6.28	6.27	6.31	3.44	3.43	3.42	5.7749
	8	0.4	114.62	114.63	114.68	6.28	6.29	6.28	3.35	3.33	3.35	5.6961
	9	0.4	114.68	114.66	114.67	6.38	6.39	6.36	3.36	3.35	3.36	5.6964
PET-G	1	0.2	114.95	114.93	114.91	6.23	6.16	6.23	3.34	3.36	3.35	5.8617
	2	0.2	114.62	114.69	114.68	6.16	6.19	6.17	3.34	3.33	3.32	5.8289
	3	0.2	115.12	115.10	115.12	6.44	6.44	6.43	3.31	3.31	3.31	5.7993
	4	0.3	114.99	115.01	115.01	6.44	6.45	6.45	3.14	3.14	3.18	5.7555
	5	0.3	115.03	115.02	115.01	6.34	6.33	6.32	3.13	3.14	3.13	5.4854
	6	0.3	114.92	114.92	114.91	6.26	6.26	6.27	3.16	3.15	3.16	5.5189
	7	0.4	115.01	114.99	115.02	6.43	6.44	6.41	3.33	3.29	3.32	5.7560
	8	0.4	115.01	114.99	114.99	6.43	6.42	6.44	3.33	3.32	3.31	5.7222
	9	0.4	114.89	114.92	114.91	6.33	6.30	6.32	3.35	3.36	3.33	5.7942
ABS	1	0.2	114.57	114.57	114.56	6.54	6.56	6.53	3.51	3.52	3.50	5.3539
	2	0.2	114.10	114.12	114.18	6.21	6.26	6.21	3.62	3.66	3.65	5.3787
	3	0.2	114.48	114.50	114.47	6.21	6.25	6.23	3.59	3.59	3.58	5.3376
	4	0.3	114.56	114.58	114.56	6.33	6.31	6.29	3.72	3.71	3.72	5.3731
	5	0.3	114.14	114.16	114.13	6.28	6.29	6.30	3.68	3.69	3.67	5.3901
	6	0.3	114.47	114.48	114.50	6.31	6.30	6.30	3.61	3.65	3.66	5.3991
	7	0.4	114.59	114.57	114.58	6.55	6.54	6.53	3.55	3.57	3.60	5.0693
	8	0.4	114.49	114.48	114.49	6.32	6.32	6.31	3.56	3.61	3.59	5.0805
	9	0.4	114.09	114.08	114.11	6.33	6.29	6.31	3.68	3.65	3.62	5.0699

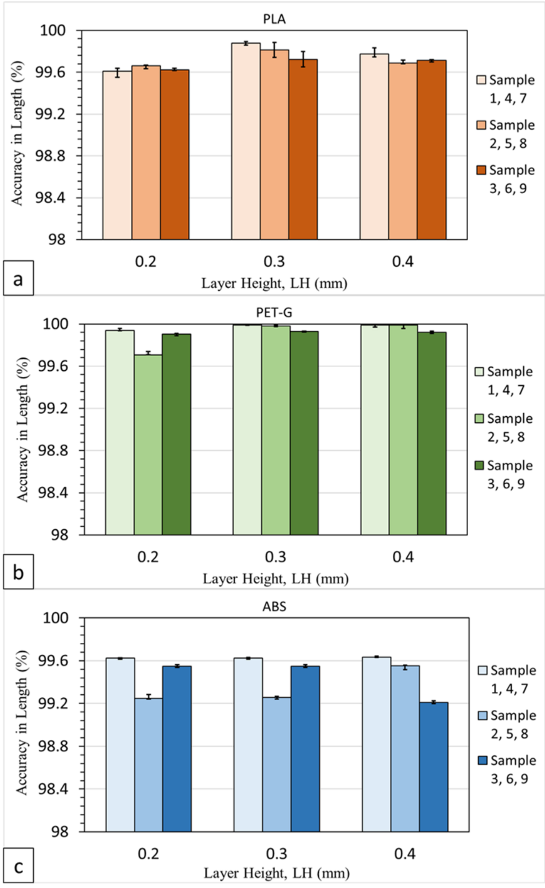

Figure 5. Accuracy values in length; PLA(a), PET- G(b) and ABS(c)

3.3. Accuracy in Width

Graphical highlights of the accuracy values in width for additively manufactured tensile samples can be followed in Figure 6. It can be brought forward by glancing at Figure 6 that accuracy results exceed almost 91% for all samples. When the comparative analyses are conducted depending on the filament type, there is no inconvenience to state that accuracy results appointed for PLA samples are more than that of the others. It can be asserted that this outcome can be clarified with the solidification process time of the polymers. For instance, in their study, Alsoufi et al. [30] expressed that ABS parts exhibited higher dimensional errors when compared with PLA parts due to the solidification process that allows more contraction. From the knowledge provided by Table 3 and Figure 6, it is inferred that the maximum average accuracy value of 97.72% is seen for the sample built with PLA whereas the minimum average accuracy value of 90.94% is recorded for the sample printed with ABS. Additionally, as long as the layer height values increase, accuracy results exhibit generally a downward trend for all types of filament materials.

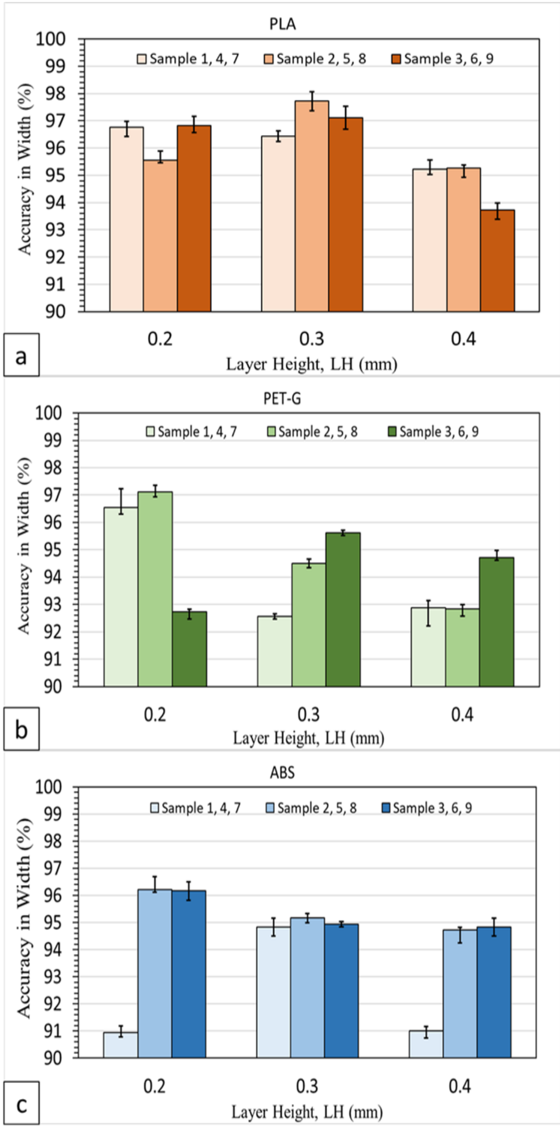

Figure 6. Accuracy values in width; PLA(a), PET- G(b) and ABS(c)

3.3. Accuracy in Height

Figure 7 demonstrates the elaborative accuracy analyses of 3D printed polymer samples. It can be understood from Figure 7 that accuracy values are above 90% for all sample types. Besides, it will be right to claim that PLA and PET-G samples display more superior outcomes than ABS samples. From Table 3 and Figure 7, it can be propounded that the highest average accuracy value of 99.11% belongs to the sample printed with PET-G. As opposed to this, the lowest average accuracy value of 90.68% is ascertained for the sample manufactured with ABS filament. As for the effect of the printing layer height, it is obvious that there is not any apparent ascending/descending relationship between accuracy and layer height. This situation can be explained by the combined impact of division availability of the design height by printing layer height and different thermal expansion/ conductivity properties of the filaments.

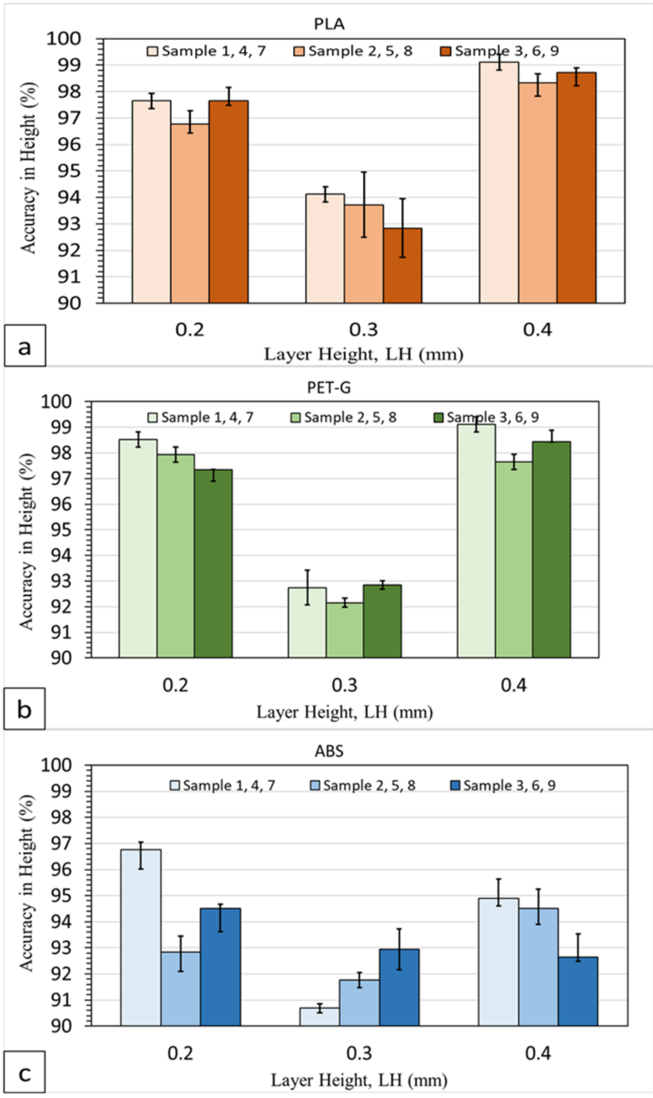

Figure 7. Accuracy values in height; PLA(a), PET- G(b) and ABS(c)

3.4. Surface Roughness Measurments

Together with the dimensional analyses, the surface roughness features of the manufactured PLA, PET-G, and ABS samples are also significant and these roughness values were measured owing to the fact that they influence the final product quality on a large scale. It is right to tell that the filament material plays a critical role in the surface roughness of the produced samples. Therefore, to reveal the differences between surface roughness values of the 3D printed samples with different filament materials, measurements were carried out perpendicular to the raster angle with a Hommel Tester T500 model profilometer as given illustration in Figure 8.

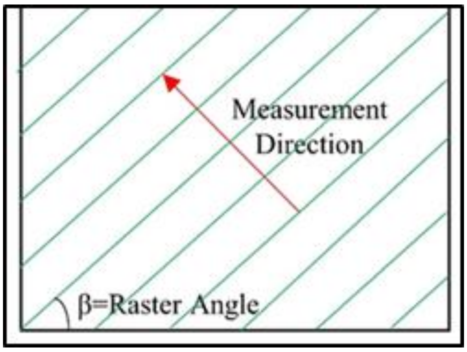

Figure 8. Schematic view of the measurement direction for surface roughness

In Figure 9, all measured surface roughness results can be examined depending upon the filament material type and printing layer height parameters. According to measured data collected as R_a criteria, the best surface quality (with 2.65 µm) belongs to samples manufactured with PLA in spite of the fact that the worst quality (with 17.3 µm) is attained for the ABS samples. Furthermore, it can be expressed looking at Figure 9 that there is an affirmative interaction between the surface roughness and printing layer height. Similar observations were also reported by Haque et al. [31]. This positive relationship between surface roughness and layer height can be explained with the difference of the top and bottom points on the path during surface roughness measurement; higher layer heights lead to a higher difference between top and bottom points on the path.

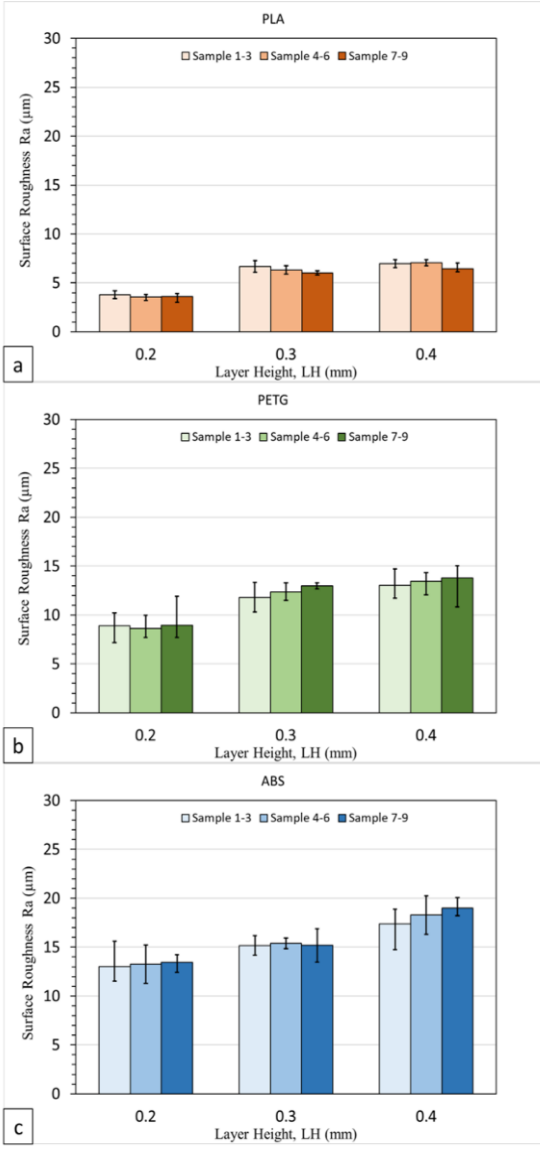

Figure 9. Surface roughness results of additively manufactured samples; PLA(a), PET-G(b) and ABS(c)

4. CONCLUSIONS

As a consequence of this work scrutinizing the dimensional accuracy success of the FFF methodology on different polymer parts by changing layer height factor, the following result remarks can be listed;

- For rapid prototyping and rapid testing, FFF is a promising methodology and different thermoplastic polymers can be comfortably produced with this technique.
- For longitudinally examination, the accuracy values reach almost 99.9% for PET-G samples because of their low thermal expansion coefficient. The accuracy results keep substantially stable with increasing printing layer height.
- Average mass values are 5.65 g (0.19 standard deviation), 5.72 g (0.13 standard deviation) and 5.27 g (0.15 standard deviation) for PLA, PET-G and ABS parts.
- From the point of width accuracy, the highest calculated average accuracy level exceeds 97.7% for the sample prepared with PLA. Also, if the printing layer height increases, the accuracy values, in particular with PET-G and ABS samples, gain a downward tendency.
- From the data collected in height analyses, it is seen that there is not a direct reciprocal correlation between printing layer height and accuracy levels of polymer parts.
- As the printing layer height elevates from 0.2 mm to 0.4 mm, measured surface roughness values also go up regardless of the polymer filament type. Besides, the best surface quality belongs to the sample produced with PLA owing to its better bonding capacity.

5. KAYNAKLAR

1. Demir, H., Gündüz, S., 2009. The Effects of Aging on Machinability of 6061 Aluminum Alloy. Materials and Design, 30(5), 1480–1483.

2. Ghosh, S., Kain, V., 2010. Microstructural Changes in AISI 304L Stainless Steel Due to Surface Machining: Effect on Its Susceptibility to Chloride Stress Corrosion Cracking. Journal of Nuclear Materials, 403(1-3), 62-67.

3. Yang, J., Yang, W., Chen, W., Tao, X., 2020. An Elegant Coupling: Freeze-casting and Versatile Polymer Composites. Progress in Polymer Science, 109, 101289.

4. Attia, U.M., Marson, S., Alcock, J.R., 2009. Micro-injection Moulding of Polymer Microfluidic Devices. Microfluids and Nanofluids, 7.

5. Bolat, Ç., Akgün, İ.C., Göksenli, A., 2020. On the Way to Real Applications: Aluminum Matrix Syntactic Foams. European Mechanical Science, 4(3), 131-141.

6. Ergene, B., Bolat, Ç., 2019. A Review on the Recent Investigation Trends in Abrasive Waterjet Cutting and Turning of Hybrid Composites. Sigma Journal of Engineering and Natural Sciences, 37(3), 989-1016.

7. Yalçın, B., Ergene, B., 2018. Analyzing the Effect of Crack in Different Hybrid Composite Materials on Mechanical Behaviors. Pamukkale University Journal of Engineering Sciences, 24(4), 616-625.

8. Novák, P., 2020. Advanced Powder Metallurgy Technologies. Materials, 13, 1742.

9. Ergene, B., 2022. Simulation of the Production of Inconel 718 and Ti6Al4V Biomedical Parts with Different Relative Densities by Selective Laser Melting (SLM) Method. Journal of the Faculty of Engineering and Architecture of Gazi University, 37(1), 469-484.

10. Ergene, B., Şekeroğlu, İ., Bolat, Ç., Yalçın, B., 2021. An Experimental Investigation on Mechanical Performances of 3D Printed Lightweight ABS Pipes with Different Cellular Wall Thickness. Journal of Mechanical Engineering and Sciences, 15(4), 8169-8177.

11. Kamer, M.S., Doğan, O., Temiz, Ş., Yaykaşlı, H., 2021. Investigation of the Mechanical Properties of Flexural Test Samples Produced Using Different Printing Parameters with a 3D Printer. Çukurova University Journal of the Faculty of Engineering, 36(3), 835-846.

12. Kumar, P., Ahuja, I.P.S., Singh, R., 2012. Application of Fusion Deposition Modelling for Rapid Investment Casting- A Review. International Journal of Materials Engineering Innovation, 3(1), 204-227.

13. Ingole, D.S., Kuthe, A.M., Thakare, S.B., Talankar, A.S., 2009. Rapid Prototyping- A Technology Transfer Approach for Development of Rapid Tooling. Rapid Prototyping Journal, 15(1), 280-290.

14. Venkataraman, N., Rangarajan, S., Matthewson, M.J., Harper, B., Safari, A., Danforth, S.C., Wu, G., Langrana, N., Guceri, S., Yardimci, A., 2000. Feedstock Material Property- Process Relationships Infused Deposition of Ceramics (FDC). Rapid Prototyping Journal, 6(1), 244-252.

15. Wohlers, T.T., 2011, Wohlers Report: Additive Manufacturing and 3D Printing State of the Industry Annual Worldwide Progress Report, Wohlers Associates, Inc., Fort Collins, CO.

16. Karabeyoğlu, S.S., Ekşi, O., Yaman, P., Küçükyıldırım, B.O., 2021. Effects of Infill Pattern and Density on Wear Performance of FDM-printed Acrylonitrile-butadiene-styrene Parts. Journal of Polymer Engineering, 41(10), 854-862.

17. Ehrmann, G., Ehrmann, A., 2021. Investigation of the Shape-Memory Properties of 3D Printed PLA Structures with Different Infills. Polymers, 13, 164.

18. Hanon, M.M., Zsidai, L., Ma, Q., 2021. Accuracy Investigation of 3D Printed PLA with Various Process Parameters and Different Colors. Materials Today: Proceedings, 42(5), 3089-3096.

19. Sood, A.K., Ohdar, R.K., Mahapatra, S.S., 2009. Improving Dimensional Accuracy of Fused Deposition Modelling Processed Part Using Grey Taguchi Method. Materials and Design, 30(10), 4243-4252.

20. Hyndhavi, D., Babu, G.R., Murthy, S.B., 2018. Investigation of Dimensional Accuracy and Material Performance in Fused Deposition Modeling. Materials Today: Proceedings, 5(11), 23508–23517.

21. Mohamed, O.A., Masood, S.H., Bhowmik, J.L., 2015. Optimization of Fused Deposition Modeling Process Parameters: A Review of Current Research and Future Prospects. Advances in Manufacturing, 3, 42–53.

22. Maurya, N.K., Rastogi, V., Singh, P., 2020. Investigation of Dimensional Accuracy and International Tolerance Grades of 3D Printed Polycarbonate Parts. Materials Today: Proceedings, 25(4), 537-543.

23. Nidagundi, V., Keshavamurthy, R., Prakash, C., 2015. Studies on Parametric Optimization for Fused Deposition Modelling Process. Materials Today: Proceedings, 2(4–5), 1691-1699.

24. Anusree, T., Anjan, R., Sivadasan, M., John, T., 2016. Process Parameter Optimization of Fused Deposition Modeling for Helical Surfaces Using Grey Relational Analysis. Materials Science Forum, 879, 861-866.

25. Wang, C.C., Lin, T.W., Hu, S.S., 2007. Optimizing the Rapid Prototyping Process by Integrating the Taguchi Method with the Gray Relational Analysis. Rapid Prototyping Journal, 13(5), 304-315.

26. Sood, A.K., Ohdar, R.K., Mahapatra, S.S., 2010. Grey Taguchi Method for Improving Dimensional Accuracy of FDM Process. AIMS International Conference on Value-Based Management, Haridwar, 608-613.

27. Alafaghani, A.A., Qattawi, A., Alrawi, B., Guzman, A., 2017. Experimental Optimization of Fused Deposition Modelling Processing Parameters: A Design-for-manufacturing Approach. Procedia Manufacturing, 10, 791-803.

28. Gonabadi, H., Yadav, A., Bull, S.J., 2020. The Effect of Processing Parameters on the Mechanical Characteristics of PLA Produced by a 3D Fff Printer. International Journal of Advanced Manufacturing Technology, 111, 695-709.

29. Zharylkassyn, B, Perveen, A., Talamona, D., 2021. Effect of Process Parameters and Materials on the Dimensional Accuracy of FDM Parts. Materials Today: Proceedings, 44(1), 1307-1311.

30. Alsoufi, M.S., Elsayed, A.E., 2018. Surface Roughness Quality and Dimensional Accuracy- A Comprehensive Analysis of 100% Infill Printed Parts Fabricated by a Personal/Desktop Cost-effective FDM 3D Printer. Materials Sciences and Applications, 9(1), 11-40.

31. Haque, M.E., Banerjee, D., Mishra, S.B., Nanda, B.K., 2019. A Numerical Approach to Measure the Surface Roughness of FDM Build Part. Materials Today: Proceedings, 18(7), 5523-5529.