Avrupa Bilim ve Teknoloji Dergisi
Özel Sayı 24, S. 119-124, Nisan 2021

Araştırma Makalesi

www.ejosat.com ISSN:2148-2683

European Journal of Science and Technology
Special Issue 24, pp. 119-124, April 2021

ResearchArticle

Experimental Investigation on the Effects of Internal Architecture on the Mechanical Properties of 3D Printed PLA Components

Cem Boğa[1*], Mirsadegh Seyedzavvar[2], Burçak Zehir[3]

[1*]Adana Alparslan Türkeş Science and Technology University, Faculty of Engineering, Department of Mechanical Engineering, Adana, Turkey,(ORCID: 0000-0002-9467-1141), cboga@atu.edu.tr

[2]Adana AlparslanTürkeş Science and Technology University, Faculty of Engineering, Department of Mechanical Engineering, Adana, Turkey, (ORCID: 0000-0002-3324-7689), mseyedzavvar@atu.edu.tr

[3]Adana Alparslan Türkeş Science and Technology University, Faculty of Engineering, Department of Mechanical Engineering, Adana, Turkey, (ORCID: 0000-0002-3143-2928), burcakzehir07@gmail.com

(2nd International Conference on Access to Recent Advances in Engineering and Digitalization (ARACONF)-10–12 March 2021)

(**DOI:** 10.31590/ejosat.901012)

ATIF/REFERENCE: Boğa, C., Seyedzavvar, M., & Zehir, B. (2021). Experimental Investigation on the Effects of Internal Architecture on the Mechanical Properties of 3D Printed PLA Components. *European Journal of Science and Technology*, (24), 119-124.

Abstract

3D printing technology is a method of fused deposition modeling (FDM) used in the aerospace industry, in light and complex structural modeling, manufacturing and prototyping of many medical tools. Polylactic acid (PLA) is used as a raw material in 3D printers due to its non-toxicity, biodegradability and easy manufacturability for industrial designs and medical applications. In this study, PLA samples were produced on a 3D printer at 70% constant filling ratio in four different filling types: line, triangle, hexagon and 3D infill. Tensile tests were performed on the samples in order to examine the effect of the filling type on the mechanical behavior. After the tests, mechanical properties of the samples such as modulus of elasticity, yield stress, maximum tensile stress and Poisson's ratio were determined. The results revealed that the filling type had significant influence on the mechanical properties of the FDM fabricated samples. It was shown that the triangle type of filling pattern in printing process yielded the highest strength to weight ratio of the fabricated sample and provided savings in raw material consumption.

Keywords: Polylactic acid (PLA), 3D printer, Filling types, Mechanical behavior, Tensile test

3 Boyutlu Basılı PLA Numunelerinin İç Mimarisinin Mekanik Davranışı Üzerindeki Etkilerinin Deneysel İncelenmesi

Öz

3D baskı teknolojisi, havacılık endüstrisinde, birçok tıbbi aletin hafif ve karmaşık yapısal modellenmesinde, üretiminde ve prototiplenmesinde kullanılan bir eriyik birikim modelleme (FDM) yöntemidir. Polilaktik asit (PLA), toksik olmaması, biyolojik olarak parçalanabilirliği, endüstriyel tasarımlar ve tıbbi uygulamalar için kolay üretilebilirliği nedeniyle 3D yazıcılarda hammadde olarak kullanılmaktadır. Bu çalışmada PLA numuneleri, 3 boyutlu yazıcıda %70 sabit doluluk oranında dört farklı dolgu tipinde üretildi: line, triangle, hexagon ve 3D infill. Dolgu tipinin mekanik davranışa etkisini incelemek için numuneler üzerinde çekme testleri yapılmıştır. Testlerin ardından numunelerin elastisite modülü, akma gerilmesi, maksimum çekme gerilmesi ve Poisson oranı gibi mekanik özellikleri belirlenmiştir. Sonuçlar, doldurma tipinin FDM yöntemi ile üretilen numunelerin mekanik özellikleri üzerinde önemli bir etkiye sahip olduğunu ortaya koymuştur. Baskı sürecinde, üçgen tip dolgu deseninde imal edilen numunenin en yüksek mukavemet/ağırlık oranını verdiği ve hammadde tüketiminde tasarruf sağladığı görülmüştür.

*Corresponding Author: cboga@atu.edu.tr

Anahtar Kelimeler: Polilaktik asit (PLA), 3D yazıcı, Dolgu türleri, Mekanik Davranış, Çekme testi

1. Introduction

Fused deposition modeling (FDM) is an additive manufacturing (AM) method commonly used for the creation of three-dimensional solid objects by enabling computer-generated models to be converted cheaply, quickly and easily into physical parts. FDM stands out with its features such as being cheaper than other AM printing technologies, being easier to maintain and having lower hardware costs [1]. FDM technologies offer rapidly developing and promising solutions in many areas of healthcare. Polylactic acid (PLA) is a biodegradable and promising 3D printable aliphatic polymer and is widely used in many fields through its rich raw materials and ease of production. Besides the industrial designs, PLA is widely used in personal protective equipment (PPE) during the COVID-19 pandemic, many specific medical applications such as implants, orthopedic applications and tissue engineering instead of the petroleum-based polymers because of its non-toxic properties [2,3]. Biodegradable and non-harmful polymers support cell growth without damaging cell functions and have strong mechanical properties. Because of these properties, it especially encourages the use and development of the PLA polymer in tissue engineering and medicine for the formation of scaffolds and bone tissues [4]. Due to this feature of PLA, it can be used in the medical industry only if it can be produced in a solid form. The thermo-mechanical properties of printed PLA samples depend on many factors including the filling pattern, filling rate and molecular structure of the material [5]. In the literature, researchers have conducted a number of studies on process parameters to investigate the mechanical properties of PLA samples. Chacón et al. [6] conducted tensile and three-point bending experiments to investigate the effect of build orientation, layer thickness and feed rate on the mechanical performance of PLA samples produced in 3D printer. They found that the upright orientation had the lowest mechanical properties and ductility decreased as the layer thickness and feed rate increased. In addition, they said that the optimum mechanical performance value can be achieved with low layer thickness and high feed rate. Yao et al. [7] produced samples at 7 different printing angles such as 0◦, 15◦, 30◦, 45◦, 60◦, 75◦, 90◦, and three different printing layer thicknesses and examined the effect of these parameters on tensile strength. As a result, they observed that increasing the printing angle and decreasing the layer thickness increased the tensile strength in the samples. Murugan et al. [8] used Taguchi experimental design method to analyze the influence of parameters such as build orientation, filling ratio, extrusion temperature, layer height and printing speed on tensile strength, Young's modulus and printing time. They found that the PLA model created with the y-axis orientation of 45 degrees gives better mechanical properties. Rajpurohit and Dave [9] investigated the effects of raster angle, layer height and raster width on tensile properties in 3D printer. They mentioned that the highest tensile strength was obtained for 0° raster angle. They found that the lower the layer height, the higher the tensile strength. They also reported that at the higher value of the raster width, the tensile strength improved to a certain extent. Camargo et al. [10] studied the mechanical properties of PLA-graphene material by producing samples of different filling ratios and layer thicknesses with 3D printing technology. As a result of their work, they stated that the mechanical properties would increase as the layer thickness increased. They stated that while mechanical properties such as tensile strength and bending strength increase as the filling ratio increases, the impact energy decreases. Khan et al. [11] made mechanical tests after producing samples with 3D printer using four different infill patterns, namely HoneyComb, HilbertCurve, Rectilinear and Concentric. They determined that the filling patterns affect the mechanical strength of the parts. After the experiments, they stated that the samples with the highest tensile and flexural strength were obtained with the Rectilinear filling pattern. Rodríguez-Panes et al. [12] investigated the effects of parameters such as layer height, filling ratio and layer orientation on the mechanical properties of PLA and ABS test specimens. They found that the percentage of filling in PLA samples is an important parameter affecting the results. They also stated that PLA samples have greater tensile strength compared to ABS. Travieso-Rodriguez et al. [13] used L27 Taguchi test sequence to find the effect of 6 parameters such as layer height, filament width, filling ratio, layer orientation, printing speed and infill pattern on the flexural strength of PLA samples. As a result, they determined that layer orientation was the most effective parameter, whereas filling density and infill pattern did not show a significant effect.

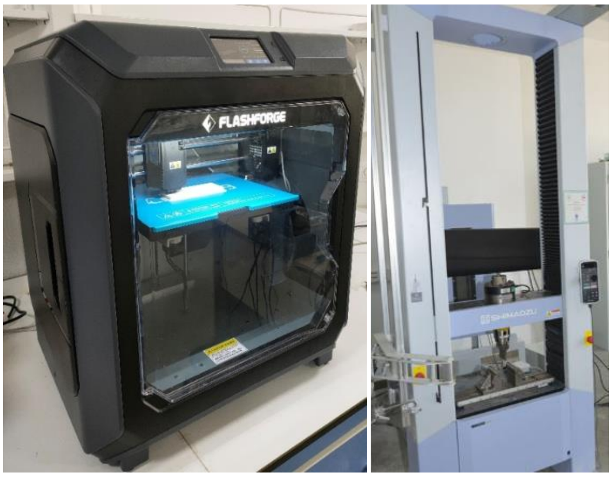
In this study, the effect of four different filling types, namely line, triangle, hexagon and 3D infill, on the mechanical behavior of PLA samples produced with a 70% constant filling ratio in a 3D printer was experimentally investigated. At the same time, mechanical properties such as yield stress, maximum tensile stress, modulus of elasticity and Poisson's ratio were obtained for these four different filling types. The strength to weight ratio has also been investigated to determine the filling type that yielded both highest strength and lowest material consumption.

2. Material and Method

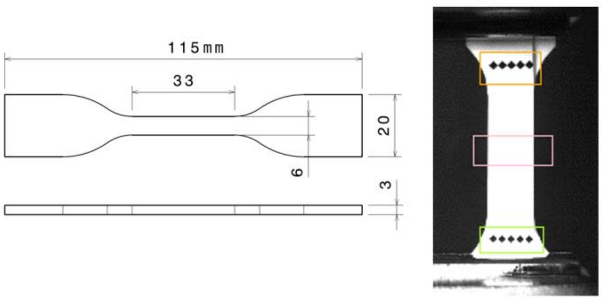
The tensile samples were produced using 1.75 mm diameter white PLA filament (Table 1), on a Flashforge Creator 3 FDM machine equipped with a 0.4 mm nozzle double extruder as shown in Figure 1a. Nozzle and bed temperatures were selected as 210 and 80 °C, respectively. In the 3D printing, the printing speed was selected as 50 mm/s and the travel speed as 70 mm/s.

Table 1. Features of employed PLA filament.

Characteristics	Value
Color	White
Printing Temperature	190-220 ºC
Density	1.25±0.05 g/cm³
Melt Flow Rate	5-7 gr/min (190 ºC 2.16 kg)
Bubble	100% no bubble
Hydroscopicity	0.50%
Hotbed Temperature	50-80 ºC (can be without hotbed)
Diameter	1.75 mm
Storage Temperature	<50 ºC



a) b)



c)

Figure 1. Experimental setup a) 3D Printer b) Shimadzu AGS-X 100 kN tensile testing machine c) Tensile test specimen.

For each filling type, 5 tensile samples were produced according to ASTM D638-14 [14] standard (Figure 1c). A total of 20 samples were produced for 4 different filling types, namely line, triangle, hexagon and 3D infill (Figure 2). The tensile tests were carried out on a Shimadzu AGS-X 100 kN tensile test machine with the constant displacement rate of 1 mm/min (Figure 1b).

All tests were carried out at room temperature. The mechanical properties of each filling type were determined by taking the average of 5 tests. Some studies in the literature say that mechanical strength is directly proportional to the filling ratio [1, 15, 16]. It is obvious that the 100% filling ratio will increase the printing cost by increasing the raw material and production time.

In order to save both processing time and cost, a lower filler ratio was selected based on the results of trial tests. After such experiments, the optimum strength to weight ratio was obtained at 70% filling ratio, so the filling ratio was selected as 70% for the rest of the test samples with different filling types.

a) b) c) d)

Figure 2. Filling types (a) line, (b) triangle, (c) hexagon, (d) 3D infill.

3. Results and Discussion

3.1 Effect of Internal Architecture on Mechanical Properties

The results of uniaxial tensile test experiments of samples fabricated in FFF process filling architecture, here called filing type, are provided and discussed in this section. The main purpose of such investigation is to examine the effects of different filling types on the yield, maximum tensile and failure stresses in 3D printed PLA samples. The stress-strain curves of such samples measured under displacement rate of 1mm/min are represented in Figure 3. The modulus of elasticity for each filling type was obtained by drawing a slope in the elastic region of the graph as in Figure 4. Also, the yield stress was determined using the 0.002 strain offset method as illustrated in Figure 4. The longitudinal and transverse deformations of the tensile test samples were measured using a digital extensometer. These data were employed to calculate the Poisson's ratio of the samples according to Eq. (1).

$$\nu = -\frac{\varepsilon_t}{\varepsilon_l} \qquad (1)$$

where ν is Poisson's ratio, ε_t is transverse strain (mm/mm) and ε_l is longitudinal or axial strain (mm/mm).

The calculated mechanical properties of the tensile test samples, including yield and ultimate strengths, modulus of elasticity and Poisson's ratio, for different filling types of 3D printed samples are summarized in Table 2. As shown in Figure 3, the triangle filling type represented the highest tensile strength compared to that of 3D infill, line and hexagon. Among these four filling types, hexagon type appears to have the lowest tensile strength value. It has been determined that the difference in tensile strength between triangle and hexagon is approximately 7.708 MPa. This result also means that the triangle type can tolerate 51.21% more loading than hexagon without failure.

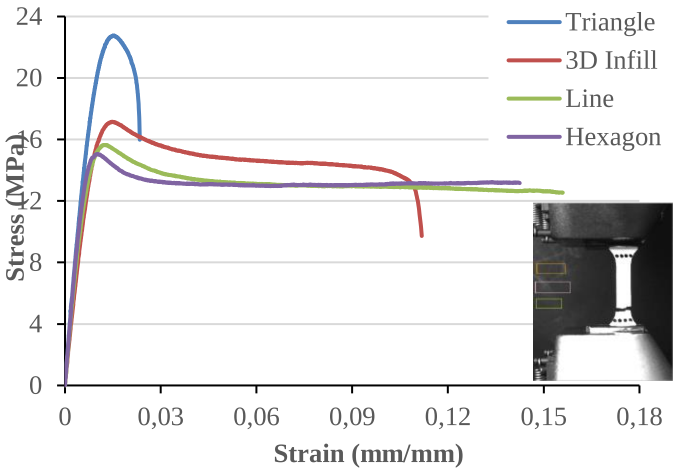


Figure 3. Comparison of tensile test results for 3D printed samples of different filling types.

From the stress-strain graph in Figure 3, it is seen that line and hexagon types have the highest failure strain values, while the line type is about 5.16% more ductile than the hexagon type. This shows that line type has the energy storage capability up to failure among different filling types. This result reveals that the line type printing pattern is more suitable for uniform distribution of applied load between the printed layers and therefore, absorption of higher strain energy before failure. For these four filling types, the modulus of elasticity values were obtained as 2, 2.3, 2.41 and 2.63 GPa for samples fabricated in FFF process using 3D infill, line, hexagon and triangle filling types, respectively. The difference between the strongest triangle and the weakest 3D infill is about 630 MPa. This indicates that the triangle filling type provides the highest elastic properties among other printing patterns of 3D printed samples. Also, the tensile samples with triangle filling type represented the highest strength without permanent deformation, or higher yield strength, among the samples fabricated by different filling patterns.

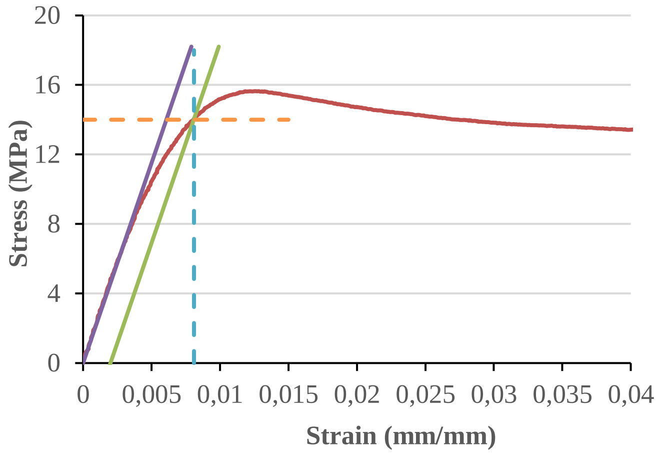


Figure 4. Representation of tangential line and 0.2% offset line on stress-stain curve to obtain mechanical properties.

Table 2. Mechanical properties of PLA samples according to internal architecture.

Materials	Yield stress (MPa)	Ultimate stress (MPa)	Modulus of elasticity (GPa)	Poisson's ratio
Line	14.0	15.64	2.3	0.213
Hexagon	14.7	15.05	2.41	0.124
Triangle	19.5	22.76	2.63	0.355
3D Infill	15.3	17.15	2.0	0.342

3.2. Effect of Internal Architecture on Strength/Weight Ratio

In order to further illustrate the effect of filling type on the mechanical behavior of 3D printing samples, it is also important to investigate the strength to weight ratio under any printing condition. The significance of latter mentioned parameter is more emphasized when the cost of printing components comes into account.

For this reason, the weight of each printed tensile sample has been measured using a digital balance with precision of 0.001 g and the sample of maximum weight has been selected as the reference sample to calculate the non-dimensional weight of each sample. Then the yield and ultimate strength of each tensile test sample has been divided to corresponding non-dimensional weight parameter to achieve the strength to weight ratio of each one these samples. The results of such measurements are summarized in Table 3. Eqs. (2-4) summarizes the calculation procedure.

$$NW_i = \frac{w_i}{w_{max}} \quad (2)$$

$$NYS/W_i = \frac{\sigma_{y,i}}{NW_i} \quad (3)$$

$$NUS/W_i = \frac{\sigma_{u,i}}{NW_i} \quad (4)$$

Where NW_i is the non-dimensional weight of i^{th} tensile test sample, w_i is the weight of sample, w_{max} is the maximum measured value of weight of samples, i represents the filling types, NYS/W_i and NUS/W_i are the yield and ultimate strengths to non-dimensional weight, $\sigma_{y,I}$ and $\sigma_{u,i}$ are the yield and ultimate stresses of sample with i^{th} tensile test sample, respectively. According to the results given in Table 3, the sample with triangle filling type represented the maximum strength to weight ratio. This shows that the triangle type can be preferred for both strength and saving of raw material.

Table 3. Non-dimensional weight and strength to weight ratio of 3D printed tensile test samples of different filling types.

Filling Types	**NW_i**	**NYS/W_i**	**NUS/W_i**
Triangle	1	19.5	22.759
Hexagon	0.9395	15.647	16.02
Line	0.9413	14.873	16.62
3D Infill	0.8541	17.914	20.083

According to the results given in Table 3, the sample with triangle filling type represented the maximum strength to weight ratio. This shows that the triangle type can be preferred for both strength and saving of raw material.

4. Conclusions

In this study, experimental tests were carried out to determine the mechanical behavior of samples produced in FFF process at different filling types. The results obtained at the end of the research can be summarized as follows:

- First of all, it has been determined that the adjustment of the parameters of the 3D printer such as nozzle and table temperatures, printing speed, travel speed and filling ratio of the samples are extremely important for production of quality parts.
- The highest tensile strength value was seen in triangle filling type and the lowest was in hexagon filling type. The results showed that samples with triangle interior architecture exhibited better tensile strength than samples with hexagon filling pattern.
- It has been observed that the line filling type is more ductile and has the highest strain at failure value.
- Modulus of Elasticity, which is a measure of the stiffness of the materials, was maximum in triangle filling type among other filling architecture.
- Triangle filling type samples are both stronger compared to other filling types and provide savings in raw material consumption.

5. Acknowledge

This article was supported by Adana Alparslan Turkes Science and Technology University Department of Scientific Research Projects with project number 20103002.

References

[1] Tanveer, M. Q., Haleem, A., & Suhaib, M. (2019). Effect of variable infill density on mechanical behaviour of 3-D printed PLA specimen: an experimental investigation. SN Applied Sciences, 1(12), 1-12. doi: https://doi.org/10.1007/s42452-019-1744-1

[2] DeStefano, V., Khan, S., & Tabada, A. (2020). Applications of PLA in modern medicine. Engineered Regeneration, 1, 76-87. doi: https://doi.org/10.1016/j.engreg.2020.08.002

[3] Farah, S., Anderson, D. G., & Langer, R. (2016). Physical and mechanical properties of PLA, and their functions in widespread applications—A comprehensive review. Advanced drug delivery reviews, 107, 367-392. doi: http://dx.doi.org/10.1016/j.addr.2016.06.012.

[4] Lopes, M. S., Jardini, A. L., & Maciel Filho, R. J. P. E. (2012). Poly (lactic acid) production for tissue engineering applications. Procedia Engineering, 42, 1402-1413. doi:10.1016/j.proeng.2012.07.534

[5] Kwapisz, M., Bajor, T., Krakowiak, M., (2019). Analysis of strength changes of PLA samples made in 3D printing technology, 28th International Conference on Metallurgy and Materials, Brno, CzechRepublic. doi: https://doi.org/10.37904/metal.2019.963

[6] Chacón, J. M., Caminero, M. A., García-Plaza, E., & Núnez, P. J. (2017). Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection. Materials & Design, 124,143-157 doi:http://dx.doi.org/10.1016/j.matdes.2017.03.065.

[7] Yao, T., Ye, J., Deng, Z., Zhang, K., Ma, Y., & Ouyang, H. (2020). Tensile failure strength and separation angle of FDM 3D printing PLA material: Experimental and theoretical analyses. Composites Part B: Engineering, 188, 107894. doi: https://doi.org/10.1016/j.compositesb.2020.107894.

[8] Murugan, R., Mitilesh, R. N., & Singamneni, S. (2019). Influence of process parameters on the mechanical behaviour and processing time of 3D printing. Int J Mod Manuf Technol, 1(1), 21-27.
[9] Rajpurohit, S. R., & Dave, H. K. (2018). Effect of process parameters on tensile strength of FDM printed PLA part. Rapid Prototyping Journal. doi: 10.1108/RPJ-06-2017-0134.
[10] Camargo, J. C., Machado, Á. R., Almeida, E. C., & Silva, E. F. M. S. (2019). Mechanical properties of PLA-graphene filament for FDM 3D printing. The International Journal of Advanced Manufacturing Technology, 103(5), 2423-2443. doi: https://doi.org/10.1007/s00170-019-03532-5
[11] Khan, S. F., Zakaria, H., Chong, Y. L., Saad, M. A. M., & Basaruddin, K. (2018, September). Effect of infill on tensile and flexural strength of 3D printed PLA parts. In IOP Conference Series: Materials Science and Engineering (Vol. 429, No. 1, p. 012101). IOP Publishing. doi:10.1088/1757-899X/429/1/012101
[12] Rodríguez-Panes, A., Claver, J., & Camacho, A. M. (2018). The influence of manufacturing parameters on the mechanical behaviour of PLA and ABS pieces manufactured by FDM: A comparative analysis. Materials, 11(8), 1333. doi: https://doi.org/10.3390/ma11081333
[13] Travieso-Rodriguez, J. A., Jerez-Mesa, R., Llumà, J., Traver-Ramos, O., Gomez-Gras, G., & Roa Rovira, J. J. (2019). Mechanical properties of 3D-printing polylactic acid parts subjected to bending stress and fatigue testing. Materials, 12(23), 3859. doi:10.3390/ma12233859
[14] D638 − 14. Standard test method for tensile properties of plastics, ASTM International, West Conshohocken, United States.
[15] Leite, M., Fernandes, J., Deus, A. M., Reis, L., & Vaz, M. F. (2018, May). Study of the influence of 3D printing parameters on the mechanical properties of PLA. In 3rd international conference on progress in additive manufacturing (Pro-AM 2018). doi:10.25341/D4988C
[16] Suteja, T. J., & Soesanti, A. (2020, July). Mechanical properties of 3D printed Polylactic acid product for various infill design parameters: A review. In Journal of Physics: Conference Series (Vol. 1569, No. 4, p. 042010). IOP Publishing. doi:10.1088/1742-6596/1569/4/042010