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The Effect of Infill Pattern on Tensile Strength of PLA Material in Fused Deposition Modeling (FDM) Process

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HIGHLIGHTS

- Ten different types of infill patterns were used.
- The concentric infill pattern has a higher effect.
- The triangles infill pattern has a lower effect.

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ABSTRACT

Fused deposition modeling (FDM) is an additive manufacturing (AM) process often used to build geometrically complex prototypes and parts. It is becoming more popular since it improves products by eliminating the need for high-priced equipment. Materials, printing methods, and printing variables all impact the mechanical characteristics of printed items. The process parameters of FDM affect the parts' quality and functionality. This study examines the influence of different infill patterns on test specimens made of polylactic acid (PLA) tensile strength. Total of 10 different infill patterns (IPs): Grid, Lines, Triangles, Tri-Hexagon, Cubic, Gyroid, Zig-zag, Concentric, Octet, and Cubic subdivision were taken as process variables. Samples were printed using processing parameters (speed 60 mm/s, layer height 0.1 mm, infill density 80%, extruded at 200◦C). The ASTM D638 tensile test was used to determine the tensile strength based on this printing parameter. According to tensile test results, the infill pattern significantly affects the tensile strength. The results showed that the concentric infill pattern has a higher tensile strength of 32.174 MPa, whereas the triangles infill pattern has a lower tensile strength of 20.934 MPa.

1. Introduction

Fused deposition modeling (FDM) is a three-dimensional printing technique that opens up new possibilities for creating parts that would be difficult or impossible to create with traditional techniques[1,2]. It works with a 3D Computer-Aided Design model to selectively join materials layer by layer to create the required component [3]. Materials such as Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) are commonly used in non-metallic 3D printing [4]. Affordability, availability, and weightlessness are why PLA has been used so widely [5]. Additionally, 3D-printed PLA has better mechanical properties than ABS [6]. The filament is typically melted and extruded in FDM systems via the machine's nozzle (3D printer). Using G-code instructions, the head of the nozzle can move in three DoFs to place the extruded polymer on the building plate. Figure 1 shows a schematic diagram illustrating the FDM process's principle. The filament is constantly fed into the extruder and nozzle of the machine using two rollers spinning in opposing directions, as shown. As a result, layers of material are deposited on the build plate before the product shape and size are reached. The printer nozzle travels back and forth through the G-code files according to the CAD model's spatial coordinates during the layering process until the component's size and structure are produced [7].

A three-dimensional CAD model is built at the beginning of the FDM process. For example, the FDM Cura software's stereolithography (STL) format exports this model into slicing software, which tessellates the part into many basic triangle components [8]. The STL format is beneficial since it simplifies geometry because the component loses some resolution during export. The software then uses this data to create an FDM machine hardware process plan, as shown in Figure 2 [9].

In 3D printing, infill plays an important role in a part's strength, structure, and weight. The structure and shape of the material inside a part are referred to as the infill pattern [10]. Many infill patterns range from easy lines to more complicated geometric shapes across different slicer programs. For example, Cura has a selection of 13 different infill patterns [11]. Tensile tests based on ASTM D638 were carried out to obtain the properties of a material based on this printing parameter [12]. According to the literature review for FDM, processes focus on infill patterns, density, layer thickness, and output tensile strength.

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Baich et al. [13] used a production-grade FDM system to evaluate the relationship between cost and time depending on the infill pattern and the required mechanical properties. Based on their results, solid infill provides higher strength performance at the same manufacturing cost as double dense infill. Farbman and McCoy [14] show that when the infill density percentage reduces, the ultimate tensile strength reduces. The ultimate tensile strength and stiffness of parts printed with hexagonal infill geometry were higher than those of printed parts with rectilinear infill geometry. The hexagonal infill part's strength is more consistent as an orientation function. Fernandez-Vicente et al. [15] examined the effect of the infill pattern (IP) and infill density on the tensile strength of an ABS 3D-printed component. Line, rectilinear, and honeycomb patterns are three different infill patterns (IPs) explored by the authors. According to the experiments, the ABS 3DP components with line and honeycomb IPs generated more tensile strength than rectilinear IP. Tensile strength is mostly determined by changes in infill density. Cho et al. [16] showed how the three-dimensional printing machine's infill pattern and layer thickness affected the mechanical strength of (PLA) material. In this research, the Taguchi Method is used to evaluate nine samples for various infill patterns (Zigzag, Triangles & Grid) and layer thicknesses (0.2, 0.1 & 0.15) mm. These results were then used to create an experiment design (DoE) for the best possible study design and quality. The layer thickness affected mechanical properties more than the infill pattern. The mechanical strength increases with increasing layer thickness. A Triangle design increases mechanical strength while using the least amount of material. The mechanical strength of a zigzag pattern is the lowest. Other variables, like unstable machine conditions or operation errors, may affect the printed output. Dezaki & Mohd Ariffin [12] examined the impact of combining infill patterns on 3D printed objects. For the tensile strength analysis of samples, five different patterns (solid, honeycomb, wiggle, grid, and rectilinear) were combined. Polylactic acid (PLA) samples were printed in two directions: flat and on-edge, with various build orientations.

The honeycomb and grid structures tested had the greatest strength-to-weight ratios while weighing less than a solid. In summary, when the build orientation is increased, strength degrades. Pandžić et al. [17] evaluated the tensile mechanical properties (tensile strength and elastic modulus) of PLA antibacterial nanocomposite, ABS-X 3D, and tough PLA printed materials when different infill densities were used (100, 80, 60, and 20 percent). For samples with 100% infill density, the cPLA material shows the highest tensile strength, 21.5% higher than tPLA and 45.6% more than ABS-X material. Also, cPLA showed the highest elastic modulus for elastic modulus, which is 21.4% higher than tPLA and 53% more than ABS-X material. For all three parts of printed material, the influence of the infill density on the tensile strength and elastic modulus can be seen. By decreasing the infill density, a linear decrease in the tensile strength value and the elastic modulus can be seen for all materials. The motivation of the present study is to introduce the best pattern configuration at a constant percentage infill equal to 80% infill for different patterns of the tensile test specimen under the same conditions.

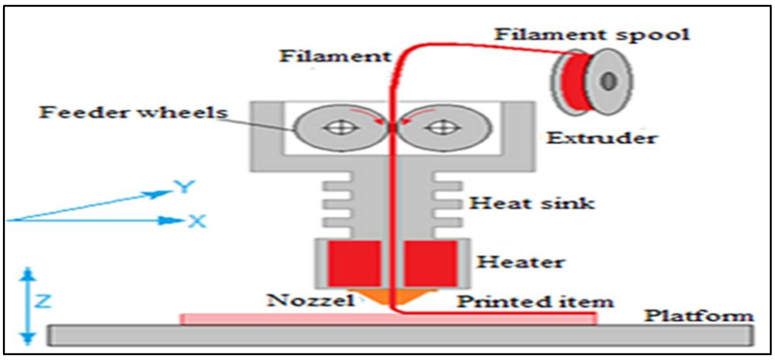


Figure 1: Principle of fused deposition modelling

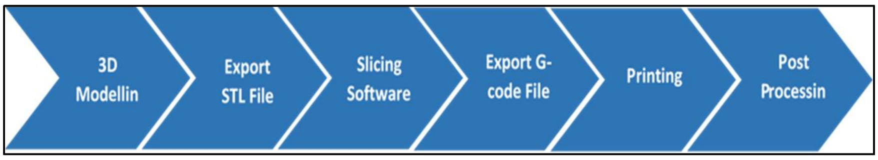


Figure 2: Flow chart of fused deposition modeling (FDM) process

2. Experimental Research and Methodology

2.1 Specimen Design

Unigraphics Solid works program was used to design specimens according to the standard specifications for each mechanical property test. Then the designs must be saved in Standard Triangle Language (STL) file form. The utility of the STL form is that the CAD packages support it. The ASTM D638 standards recommend Type I dimensions for this experiment, shown in Figure 3.

In addition to these dimensions, the gage length of 50 mm and a distance between grips of 115 mm. To create the 3D model of the part specimen, SolidWorks modeling software was used, as shown in Figure 4, and then translated into the STL format, as shown in Figure 5.

Next, we imported the STL file into the slicing program and used the available choices to design the experiment. The user may now adjust the printing parameters such as orientation, layer thickness, and print speed. As soon as the settings are suitable, the program will slice the model and produce the necessary tool path information, as shown in Figure 6. Finally, the printer may move the nozzle and print the component using this data.

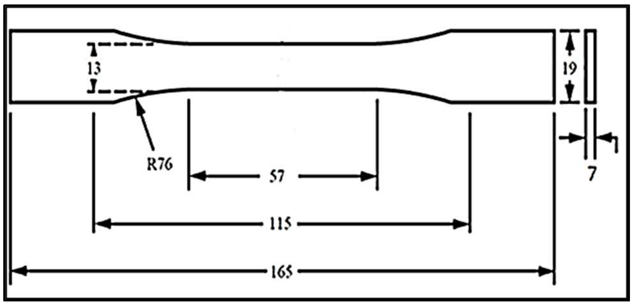


Figure 3: Dimensions used for 3D printed tensile specimen [18]

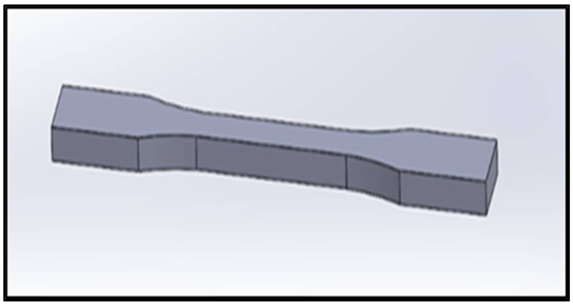


Figure 4: SolidWorks model of the parts specimen

Figure 5: STL files of the SolidWorks model

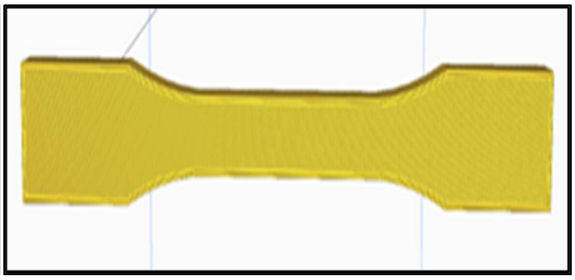


Figure 6: Slicing of the parts in Cura software

3. Materials

This research uses wire filament made from PLA, a commercially available material made in China by Shenzhen Esun Industrial Co., Ltd, for printing samples. Polylactide (PLA) is a biodegradable and bioactive polyester made up of lactic acid building blocks. It is the default filament of choice for most extrusion-based 3D printers because it can be printed at a low temperature and does not require a heated bed. PLA is easy to print, very inexpensive, and creates parts that can be used for various applications. It is also one of the most environmentally friendly filaments on the market today, renewable, and most importantly, biodegradable. However, PLA has a limitation due to its inherent brittleness [19].

4. Process Parameters

In this research, the infill pattern differs by keeping parameters such as infill density, layer thickness, and printing speed constant. Each layer of the 3D print is supported by an infill pattern, which is built by the printer. Printing the layers would be tedious without an infill pattern because the material would droop over the print's empty parts. The infill patterns selected for this study is Grid, Lines, Triangles, Tri-Hexagon, Cubic, Gyroid, Zig-zag, Concentric, Octet, and Cubic subdivision. Infill density refers to the percentage of molten material filled with building a product. Layer thickness is a measure of the height of the layer of each sequential addition of material stacked. Finally, printing speed is measured by the amount of manufactured material over time.

5. Process Flow

The experiment's process flow is shown in Figure 7.

1) Phase one begins with creating the specimen's standard sample design in the solid works modeling program.
2) The STL file for this design has been created.
3) This STL file is processed via Cura software, where many settings like temperature, layer thickness, pattern, and so forth are defined.
4) Then convert it to G-code so that a 3D printer may create a working model of it.
5) Use a 3D printer to create the test specimen.
6) Put them in a tensile test machine, conduct tests, and document the results.

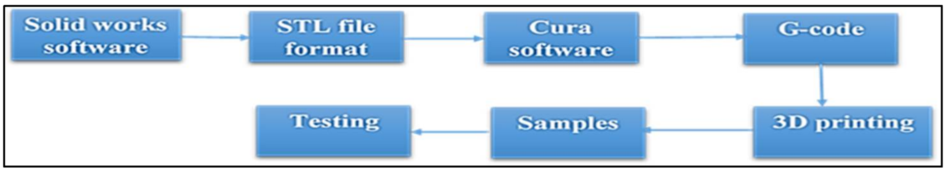
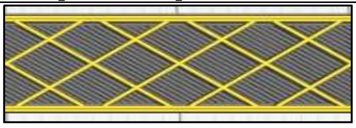
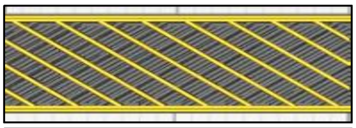
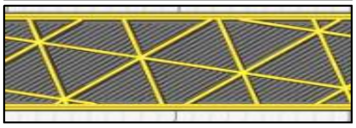
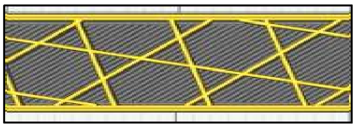
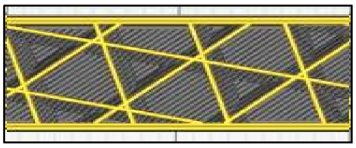
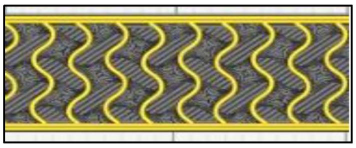
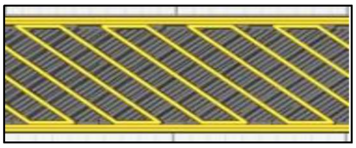
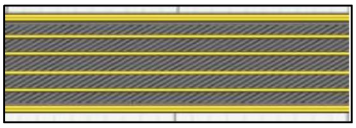
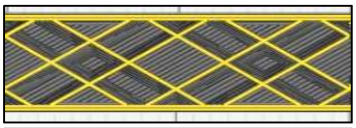
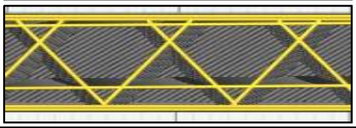


Figure 7: Diagram Flow Chart of Experiment

6. Preparation

Solidworks for product design and Cura for parameter selection was used in the project preparation process. Following our design, we drew in SolidWorks and then converted the STL file to provide data to the Cura program. As shown in Table 1, distinct patterns emerge when Cura is simulated.

Table 1: Infill patterns of specimen in simulation in Cura software

Specimen number	Infill type	Infill pattern shape
1	Grid	
2	Lines	
3	Triangles	
4	Tri-Hexagon	
5	Cubic	
6	Gyroid	
7	Zig Zag	
8	Concentric	
9	Octet	
10	Cubic Subdivision	

7. Printing

Samples created in Solidworks and Cura must be printed using a Fused Deposition Modelling (FDM) 3D printer once they have been designed (Ender 5). As previously mentioned, we utilized PLA to construct samples for our product. To create 3D printing G-code for a 3D printer, the parameters that must be entered into the Cura program are shown in Table 2.

A total of ten 3D-printed specimens will be used in the testing process. The printing conditions for each specimen are shown in Figure 8. After printing was complete, all samples were marked and calibrated using equipment to verify their dimensions and thickness before going through the tensile testing procedure.

Table 2: Fixing parameters

Parameters	Value	Units
Printing speed	60	mm/sec
Infill density	80	%
Printing temperature	200	Degree Celsius
Shell wall thickness	1	Mm
Layer thickness	0.1	Mm
Build plate temperature	50	Degree Celsius

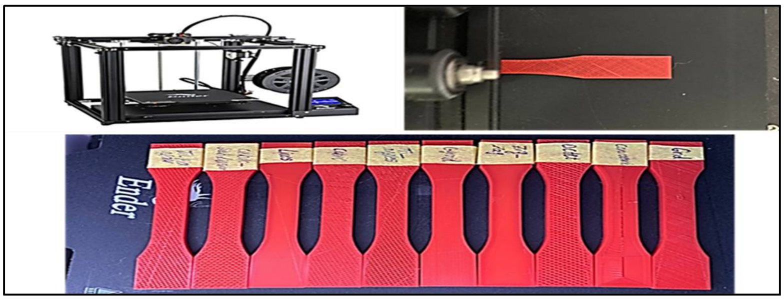


Figure 8: 3D printing of infill pattern of test specimen on (Ender 5) 3D printer

8. Tensile Test

The tensile test determines the samples' stress, strain, and Young's modulus at a certain tension. ASTM D638 and the Universal Testing Machine WDW-2006 are utilized to perform the test. There is a 1.5 mm/mins crosshead speed or strain rate employed. The Vernier caliper measures the sample's dimension before the tensile test to calculate the samples' stress, strain, and Young's modulus. The fundamental concept behind a tensile test is to clamp a piece of material between two fixtures called "grips". Before applying weight to the material gripped at one end while the other remains stationary, its dimensions, such as length and cross-sectional area, are known. Increasing the weight, also known as the load or the force, and measuring the sample's length change simultaneously. Using a machine to do the testing, export data to PDF and Excel files, which can then be compared for use in further experiments.

9. Results and Discussion

9.1 Tensile Test Results

All the samples are tested properly, and the experimental readings are tabulated in Table 3. The specimens after testing are shown in Figure 9; the graph between infill pattern and tensile strength is plotted and shown in Figure 10. When comparing infill geometry, the Test Works program used load-elongation data to do a series of calculations in Excel. The table below summarizes the findings of the tests conducted on the 10 different combinations. Using the average measurement results of the 10 samples, the ultimate strength values were calculated according to ASTM standards. Then, using 10 various infill patterns, the stress and strain values of PLA were compared to see which was the strongest. Stress-strain diagrams are shown in Figure 11 for ten different patterns of PLA infill.

According to the results of the experiments, the FDM 3D printed tensile strength showed that a concentric pattern with 80% infill density and 0.1 mm layer thickness showed the highest tensile strength, with a value of 32.174 Mpa Figure 12 illustrates a specimen with a concentric infill pattern. This is due to the objects being flexible and can be twisted without experiencing any significant damage or deformation to the overall shape in the concentric pattern where beads are deposited along the specimen's length in a direction parallel to the applied load. Since more layers were pulled longitudinally, the concentric infill pattern exhibited ductile behavior, with significant plastic deformation and near values for tensile stress for both patterns. Under the same infill density and layer thickness, the cubic pattern shows the second-highest tensile strength with a value of 26.601 MPa. This incongruity could be attributed to slight variations in the amount of plastic deposited for each pattern. The cubic infill pattern has a greater tendency to hold its intermolecular layers. The discharging trajectories and the interlayer bonding zones are highly different between cubic and concentric infill patterns. In a concentric infill pattern, only one direction is printed per layer. However, the mechanical behaviors between the above mesostructures are similar. Rismalia et al. [6], Dave et al. [20], and Pandzic et al. [21] have reported a similar effect of concentric patterns on tensile properties.

Table 3: Tensile strength of various infill patterns

No. of test	Infill pattern	Tensile strength (MPa)
1	Triangles	20.934
2	Gyroid	23.085
3	Cubic	26.601
4	Lines	24.799
5	Concentric	32.174
6	Zig-zag	25.621
7	Octet	24.030
8	Grid	21.702
9	Tri-hexagon	21.036
10	Cubic-subdivision	22.130

Figure 9: Specimens after tensile test

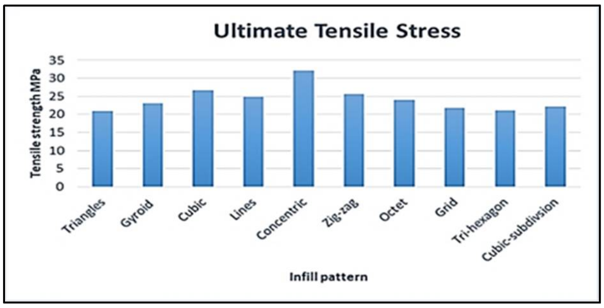


Figure 10: Tensile Strength vs. Infill Pattern

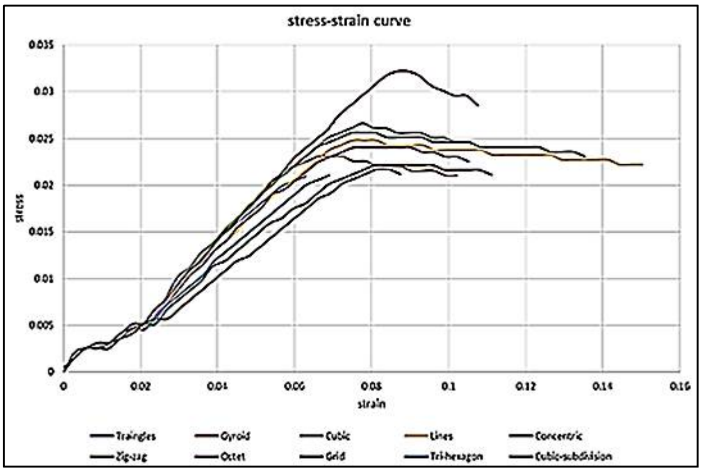


Figure 11: Stress-strain curve

Figure 12: Concentric infill pattern

Finding the maximum value on the stress vs. strain diagram will give you the ultimate stress value quickly and efficiently. Among the 10 specimens, the infill pattern with the lowest tensile strength is the triangles infill pattern. Since it contains lines printed in three directions, it cannot bear much tensile strength, which makes it break easily while applying tensile load. After triangles infill, the grid followed by the tri-hexagon infill pattern has the lowest tensile strength, with values of 21.702 MPa and 21.036 MPa. Thus for building a 3D printed part or specimen of PLA material using the FDM technique, which can bear high tensile strength, a concentric infill pattern is preferred for a better outcome under the selected operating conditions.

10. Conclusion

In this research, the effect of the selected infill pattern on the FDM process parameters and keeping all other parameters at the same level, the tensile strength of PLA filament-fabricated parts was experimentally analyzed, and the following conclusions were found:

1) The tensile strength properties of FDM printed parts are impacted by the infill pattern process parameters.
2) The concentric infill pattern demonstrated the highest tensile properties, while the grid and tri-hexagon patterns are at similar levels. The value of tensile strength of 32.174 MPa was documented for the concentric pattern. This is due to the result of longitudinal beads.
3) The concentric infill pattern is much more compact than other patterns since the infill prints from the outside towards the center of the model, making the infill lines too close to each other. This would increase the consistency of print layers.
4) Triangles infill pattern gives less tensile strength with a value of 20.934 MPa since the interlayers can't bear much tensile strength, making them break easily while applying tensile load.
5) The form of the infill has a significant role. Many mechanical characteristics, including modulus, yield stress, ultimate tensile stress, and percent elongation, were found to be influenced by the form. In addition, the stress vs. strain diagrams changed in form because of this.

In future examinations, the infill pattern should be chosen based on mechanical performance, printing time, and materials costs. The findings may be utilized to create a finite element model (FEM) and estimate the best tensile characteristics for printing parameters selected based on the reference data. In addition, the influence of infill patterns on other mechanical properties, such as compressive strength, bending strength, and torsional strength, will be investigated.

Author contribution

All authors contributed equally to this work.

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Data availability statement

Data supporting reported results can be found on google scholar.

Conflicts of interest

The authors declare no conflict of interest. The funders had no role in the study design, collection, analyses, interpretation of data, writing of the manuscript, or in deciding to publish the results.

References

[1] S. Fafenrot, N. Grimmelsmann, M. Wortmann, A. Ehrmann, Three-dimensional (3D) printing of polymer-metal hybrid materials by fused deposition modeling, Materials ,10 (2017) 1199. https://doi.org/10.3390/ma10101199

[2] S. M. Ahmad , S. Y. Ezdeen, Effect of coating on the specific properties and damping loss factor of ultem 1010, Zanco J. Pure Appl. Sci.,33 (2021) 105–116. https://doi.org/10.21271/ZJPAS.33.2.10

[3] T. Abbas, F. M. Othman, and H. B. Ali, Effect of infill Parameter on compression property in FDM Process, dimensions, 12 (2017) 24–25. https://doi.org/10.9790/9622-0710021619

[4] F. A. Naser , M. T. Rashid, The Influence of Concave Pectoral Fin Morphology in The Performance of Labriform Swimming Robot, Iraqi J. Electr. Electron. Eng., 16 (2020) 54–61. https://doi.org/10.37917/ijeee.16.1.7

[5] N. A. Aldeen, B. A. Sadkhan, and B. Owaid, Hand bone orthosis manufacturing using 3d printing technology, J. Eng. Sustain. Dev. ,24 (2020) 451–458. https://doi.org/10.31272/jeasd.conf.1.50

[6] M. Rismalia, S. C. Hidajat, I. G. R. Permana, B. Hadisujoto, M. Muslimin, F. Triawan, Infill pattern and density effects on the tensile properties of 3D printed PLA material, J. Phys. Conf. Ser.,1402 (2019) 44041. https://doi.org/10.1088/1742-6596/1402/4/044041

[7] F. M. Mwema, E. T. Akinlabi, Fused Deposition Modeling: Strategies for Quality Enhancement. Springer Nature, 2020. https://doi.org/10.1007/978-3-030-48259-6

[8] W. A. Soud, I. A. Baqer, M. R. Ahmed, Experimental Study of 3D printing Density Effect on the Mechanical Properties of the Carbon-Fiber and Polylactic Acid Specimens, Eng. Technol. J., 37 (2019) 128–132. https://doi.org/10.30684/etj.37.4A.3

[9] F. M. Othman, T. Fadhil, A. H. B. Ali, Influence of process parameters on mechanical properties and printing time of FDM PLA printed parts using design of experiment, J. Eng. Res., 8 (2018) 2248–9622. https://doi.org/10.9790/9622-080702656965

[10] R. Srinivasan, K. N. Kumar, A. J. Ibrahim, K. V Anandu, R. Gurudhevan, Impact of fused deposition process parameter (infill pattern) on the strength of PETG part, Mater. Today Proc., 27 (2020) 1801–1805. https://doi.org/10.1016/j.matpr.2020.03.777

[11] B. Huang, S. Meng, H. He, Y. Jia, Y. Xu, H. Huang, Study of processing parameters in fused deposition modeling based on mechanical properties of acrylonitrile-butadiene-styrene filament, Polym. Eng. Sci., 59 (2019) 120–128. https://doi.org/10.1002/pen.24875

[12] M. Lalegani Dezaki , M. K. A. Mohd Ariffin, The Effects of Combined Infill Patterns on Mechanical Properties in FDM Process, Polymers, 12 (2020) 2792. https://doi.org/10.3390/polym12122792

[13] L. Baich, G. Manogharan, H. Marie, Study of infill print design on production cost-time of 3D printed ABS parts, Int. J. Rapid Manuf., 5 (2015) 308. https://doi.org/10.1504/IJRAPIDM.2015.074809

[14] D. Farbman , C. McCoy, Materials testing of 3D printed ABS and PLA samples to guide mechanical design, Int. J Manuf Sci Eng. Conf., 2016, 12. https://doi.org/10.1115/MSEC2016-8668

[15] M. Fernandez-vicente, W. Calle, S. Ferrándiz, A. Conejero, Effect of Infill Parameters on Tensile Mechanical Behavior in Desktop 3D Printing, 3D Print. Addit. Manuf., 3 (2016) 183–192. https://doi.org/10.1089/3dp.2015.0036

[16] E. Cho, H. Hein, Z. Lynn, S. Hla, T. Tran, Investigation on Influence of Infill Pattern and Layer Thickness on Mechanical Strength of PLA Material in 3D Printing Technology, J. Eng. Sci. Res., 3 (2019) 27–37. https://doi.org/10.26666/rmp.jesr.2019.2.5

[17] A. Pandžić, D. Hodžić, E. Kadrić, Experimental Investigation on Influence of Infill Density on Tensile Mechanical Properties of Different FDM 3D Printed Materials, TEM J., 10 (2021) 1195-1201. https://doi.org/10.18421/TEM103-25

[18] American Society for Testing and Materials, ASTM D638-14, Standard Practice for Preparation of Metallographic Specimens, ASTM Int., 82 (2016) 1–15. https://doi.org/10.1520/D0638-14.1

[19] Y. F. Buys, A. N. A. Aznan, H. Anuar, Mechanical properties, morphology, and hydrolytic degradation behavior of polylactic acid/natural rubber blends, IOP Conf. Ser. Mater. Sci. Eng., 290 (2018) 12077. https://doi.org/10.1088/1757-899X/290/1/012077

[20] H. K. Dave, N. H. Patadiya, A. R. Prajapati, S. R. Rajpurohit, Effect of infill pattern and infill density at varying part orientation on tensile properties of fused deposition modeling-printed poly-lactic acid part, Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci., 235 (2021) 1811–1827. https://doi.org/10.1177%2F0954406219856383

[21] A. Pandzic, D. Hodzic, A. Milovanovic, Effect of infill type and density on tensile properties of PLA material for FDM process, Ann. DAAAM Proc., 30 (2019) 0545-0554. https://doi.org/10.2507/30th.daaam.proceedings.074