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Investigation and Prediction of the Impact of FDM Process Parameters on Mechanical Properties of PLA Prints

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HIGHLIGHTS

- Nine specimens were 3D printed using various parameters and ASTM standards (D695, D638-02a).
- Influence of printing parameters, such as infill pattern, density, and layer thickness, on strength was explored.
- Infill density was found to significantly affect both compressive and tensile strength.

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ABSTRACT

Complex geometry components can be produced using FDM-based additive manufacturing (AM). In this study, the compressive and tensile strength were investigated, considering variations in layer thickness (0.2, 0.25, and 0.3 mm), density (40%, 60%, and 80%), and infill pattern (tri-hexagon, zig-zag, and gyroid). The experiment was designed using the Taguchi technique and carried out on a commercial FDM 3D printer, involving nine specimens with different processing settings. The compression standard ASTM D695 and tension standard ASTM D638-02a were used for evaluation. The results indicated that infill density significantly impacted compressive and tensile strength, contributing to 65% and 60% of the variations. Based on the S/N ratio analysis, the optimal parameters for achieving high compressive and tensile strength were 80% infill density, a Gyroid infill pattern, and a layer thickness of 0.3 mm. With these settings, the maximum compression strength reached 45.23 MPa, and the maximum tensile strength was 44.03 MPa. Regression prediction modeling proved to be a powerful tool for predicting the compression and tensile strengths of PLA samples and optimizing the 3D printing process. Accurate and reliable predictions can be achieved by carefully selecting relevant features, preprocessing the data, training, and evaluating the model. These predictions can greatly assist in process design and manufacturing, with a percentage error of approximately 2.79% for compression strength and 3.35% for tensile strength.

1. Introduction

Due to its flexibility, simplicity, and portability, rapid or additive manufacturing is an advanced manufacturing technique [1]. Fused deposition modeling is a common additive manufacturing method for polymeric 3D printing items. It's a fast, accurate, and affordable 3D printing method. This method also uses many structures and intricate geometries.

The effect of infill ratio and pattern in 3D-printed using polylactic acid (PLA) polymer compressive strength and hardness. 3D-printed samples were made using FDM. Each variety had three specimens with different infill ratios (30%, 50%, and 70%) and patterns (line, gyroid, and trihexagon). A general-purpose manual compression testing machine followed EN772-1 and ASTM D695 standards for blocks, cubes, and cylinders. Following ASTM D2240-05 (2010) type D, a Shore Instruments Type D hand-held durometer tested hardness. Data showed that a 70% infill ratio and a linear design had the maximum compressive strength. The creatures' bases were the hardest [2].

Analyzes how varied infill patterns affect PLA tensile strength test specimens. Process variables included ten types of infill patterns. Samples were printed at 60 mm/s, 0.1 mm layer height, 80% infill density, and 200°C extrusion. This printing parameter determines the tensile strength using the ASTM D638 tensile test. Tensile test findings show that infill patterns greatly impact strength. The concentric infill pattern has 32.174 MPa tensile strength, whereas the triangular pattern has 20.934 MPa [3]. Infill pattern type, density, and layer thickness affect ABS compressive strength at three levels. The Taguchi technique was used to design the experiment. A commercial FDM 3D printer produced nine specimens with varying processing settings and evaluated them according to ASTM D695. This study found that printing factors affect compressive strength. An analysis of variance showed that infill density is the most affected of the three factors—The maximum compression strength of 44.64 MPa [4]. FDM nozzles melt and extrude filament. Using a G-code, the nozzle head may move in three DoFs to arrange extruded polymer on the

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construction plate. Two opposed rollers feed filament into the machine's extruder and nozzle. [5], layers of material are deposited on the build plate before product form and size are determined. During layering, the printer nozzle follows the CAD model's spatial coordinates using G-code files to create the component's size and structure [6].

FDM starts with a 3D CAD model. FDM Cura's stereolithography (STL) format transfers this model to slicing software, which tessellates it into numerous triangular components [7]. Due to export resolution loss, the STL format reduces geometry. A computer programmer slices a component's CAD model into single layers with a set thickness to construct its shape in FDM [8]. 3D CAD is used to create a model, which is then converted to a Standard Tessellation Language (STL) file, sliced into a G-code file, and printed on an FDM 3D printer [9]. FDM can rapidly build complicated geometrical forms and structures [10]. Infill percentage, layer thickness, build orientation, and other FDM print variables affect the mechanical qualities and construction time of the finished 3D item [11]. 3D-printed items' mechanical qualities depend on process settings and raw material properties [12]. The last layer thickness (0.178 mm) maximizes item performance [13]. Another investigation indicated that as layer thickness increased, specimen tensile strength declined, then increased [14]. When strong compression force is needed, the rectangular pattern at 0° and 90° is ideal for ABS polymer [15]. Infill geometry (rectangular, triangular, diamond, and hexagon) was tested for compressive strength. Infill geometries affect 3D-printed item compression strength and elastic modulus [16]. The research found that increasing infill density reduced cavities and increased strength [17].

This study uses the Taguchi technique to discover the best FDM 3D printer parameters (infill pattern, density, and layer thickness) for high-compressive and high-tension PLA products. The infill density is the largest critical parameter that affects the 3D printing compression and tension processes.

2. Experimental Work

2.1 Filament Used

Printing uses a 1.75-mm polylactic acid (PLA) filament. PLA, a thermoplastic monomer composed of lactic acid and the cyclic di-ester lactide, is sustainable and organic. PLA manufacturing is unique since biomass is used. Changing its component ratio or fabrication method may change its characteristics. PLA has strong chemical, mechanical, and impact strengths.

2.2 Selecting Process Parameters

Samples were made from PLA. All experimental samples were printed using FDM 3D printer's Ender 3, which displays three FDM parameters: infill density (40%, 60%, and 80%), layer thickness (0.2, 0.25, and 0.3 mm), and infill pattern type (Zig-Zag, Gyroid, and Tri-Hexagon).

- Infill density: the print's inner plastic. Higher infill density uses more plastic within your print.
- Layer thickness: the object's layer thickness.
- Infill pattern: material structure and contour. Infill patterns affect strength, weight, print time, and flexibility. Lines to complicated geometric forms are possible.

2.3 The Design of The Experiment

The Taguchi Technique analyzes parameter interactions using an orthogonal array. Each experiment specifies parameter combinations and levels. The Taguchi approach uses orthogonal arrays to evaluate process quality with a few experiments [12]. The Taguchi technique uses an orthogonal array to find the optimal control parameters by testing response variables' affectability to a combination of control settings [18]. This experiment used the L9 array, with parameter values in Table 1.

The S/N ratio establishes control factor settings to limit noise factor volatility [19]. The best experimental variables limit product variance around the goal value, maximum S/N [20]. The experiment maximizes the response of the signal-to-noise ratio shown in Equation 1, determining that "Larger is better" for static designs utilized for quality attributes in this study.

$$S/N = -10 \times \log(\sum(1/Y2)/N) \tag{1}$$

where the response variable (compressive strength) is Y.

Table 1: The experimental design using Taguchi

Experiment No.	Infill density (%)	Parameter levels Infill pattern	Layer thickness (mm)
1	40	Tri-hexagon	0.20
2	40	Zig-Zag	0.25
3	40	Gyroid	0.30
4	60	Tri-hexagon	0.25
5	60	Zig-Zag	0.30
6	60	Gyroid	0.20
7	80	Tri-hexagon	0.30
8	80	Zig-Zag	0.20
9	80	Gyroid	0.25

2.4 3D Printer Machine

Figures 1 and 2 shows a 3D CAD geometric model created as a tensile test specimen using ASTM D638-02a specifications (Type I specimen, thickness 7 mm) using the tensile sample; ASTM D 695 specifies using the compression sample.

As illustrated in Figures 3 and 4, samples were printed with a diameter of the nozzle (0.5 mm), a temperature of extrusion of (205ºC), a temperature of bed (45ºC), a thickness of shell (1.0 mm,) and a printing speed of (90 mm/s) on a Reality Ender 3 FDM machine. PLA filament with a (1.75 mm) diameter is printed. The strength at break of a compressive and tension property using the same machine as that of a tensile property. For compression tests, use global computerized testing equipment with a (5) ton-force (metric) capacity and a 5 mm/min constant value speed. Samples were compressed quasi-statically until failure displayed the (9) test that was compressed and represented by each Taguchi orthogonal array experiment.

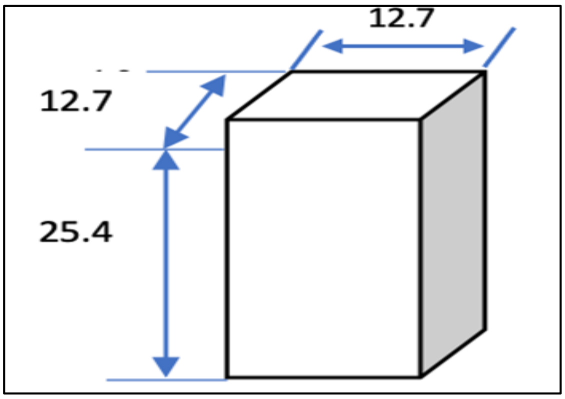

Figure 1: A specimen of compressive strength (all dimensions are in mm) [21]

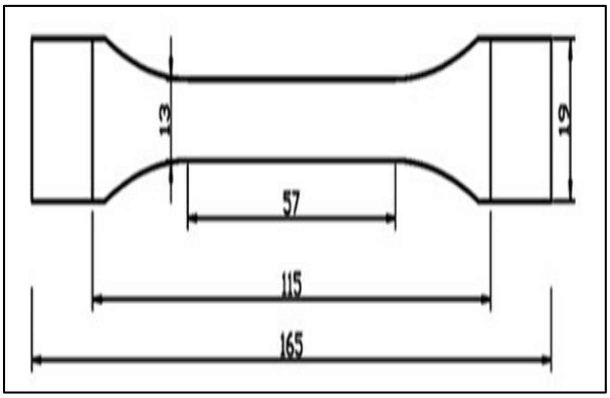

Figure 2: A specimen of tension strength (all dimensions are in mm) [22]

Figure 3: Compression test run samples

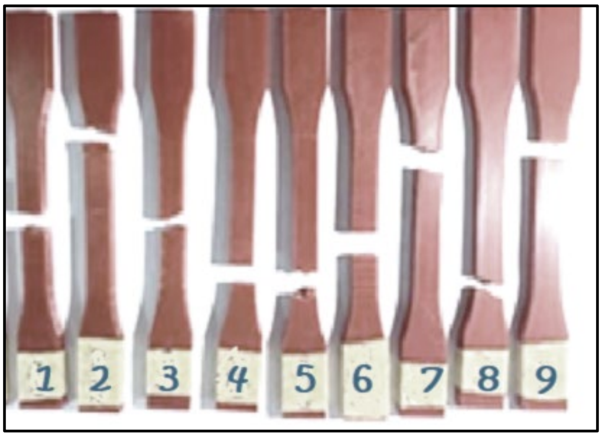

Figure 4: Compression test run samples

3. Results and Discussion

Table 2 shows all nine PLA 3D-printed sample compression and tension test results and S/N ratios. Each orthogonal array experiment represented a sample. Experiment no.9 (80%, 0.3 mm, Gyroid) had the maximum compression and tensile strength because of the large infill density, which occurs in large support, and the use of gyroid pattern type with a high 0.3 mm for each layer was given stronger than the other Experiment.

Tables 3 and 4 show how each rank affects compression and tensile strength, respectively. Infill density affects compressive strength the most, followed by infill pattern and layer thickness. The fill with 80 % is like a solid part, so it has more strength effect than another parameter. Figure 5 display the S/N ratio major effects plot, showing the independence of the S/N ratio choice (bigger is preferable). Gyroids improve compressively.

According to research, mechanical qualities improve as infill density, type of infill shape, and rise. Layer thickness increases compressive strength [23,24]. The layer thickness of (0.3 mm), infill density of 80%, and infill pattern of Gyroid were best for compressive strength. Table 4 shows how much each element contributed to the answer (compressive strength) from the S/N ratio analysis of variance. Figure 6 shows that infill density contributed (65%), pattern (22%), and layer thickness (10%). Infill density, full pattern, and layer thickness are important parameters in 3D printing that can significantly affect the mechanical properties of printed parts, including their behavior under compression and tension. Infill density refers to the amount of material used to fill the interior of a 3D-printed part. It is typically expressed as a percentage ranging from 0% (hollow) to 100% (solid). Generally, a higher infill density will result in a stronger and more rigid part, but it will also take longer to print and use more material.

According to Tables 4 and 5, the analysis of the S/N values can be separated for each process response parameter. In specimens with gyroid infill patterns, printing continuously in one diagonal direction cause stronger inter-raster bonding with a tiny raster gap and allows more consistent adhesion between the layers.

The infill density is an important process parameter that significantly affects the mechanical properties. The best mechanical properties are obtained when the infill density of the specimens is large at 80%.

The layer parameter was shown to affect the strength of components directly. Because of the significant voids present inside the components, this connection may not hold for sections with low infill densities.

Table 2: Taguchi design (L9) compression and tension strength signal-to-noise ratio

No	Density	Pattern type	layerthicknss	Compressive strength (MPa)	S/N Ratio	Prediction Compressive strength	tension strength (MPa)	S/N Ratio	Prediction tension strength
1	40	Tri-Hexagon	0.20	22.41	26.0858	18.4444	21.29	25.5638	17.1767
2	40	Zigzag	0.25	21.06	26.7775	22.2244	20.99	26.5572	21.6067
3	40	Gyroid	0.30	23.99	28.2153	26.7911	21.19	27.4053	24.6867
4	60	Tri-Hexagon	0.25	28.88	29.8266	31.6811	27.65	29.7166	31.1467
5	60	Zigzag	0.30	39.55	31.0199	35.5844	38.51	30.7118	34.3967
6	60	Gyroid	0.20	32.73	30.6073	33.8944	31.37	30.0473	31.9867
7	80	Tri-Hexagon	0.30	38.01	31.9063	39.1744	37.28	31.5465	37.8967
8	80	Zigzag	0.20	34.02	31.2493	36.8211	32.16	31.0290	35.6567
9	80	Gyroid	0.25	45.23	32.1855	41.2644	44.03	31.8753	39.9167

Table 3: The signal-to-noise ratio for compression testing

Level	Infill density	Infill pattern	Layer thickness
1	26.11	28.90	28.67
2	29.01	28.45	28.76
3	30.56	29.14	29.23
Delta	4.59	1.12	0.94
Rank	1	2	3

Table 4: S/N ratio ANOVA for compression

Source of variance	DOF	Sum of squares	Variance	P (%)
density	2	365.6	182.8	65.55%
Pattern type	2	125.2	62.6	22.45%
layer thickness	2	57.06	28.5	10.23%
Error,e	6	8.9		1.6%
Total	8	557.8		100

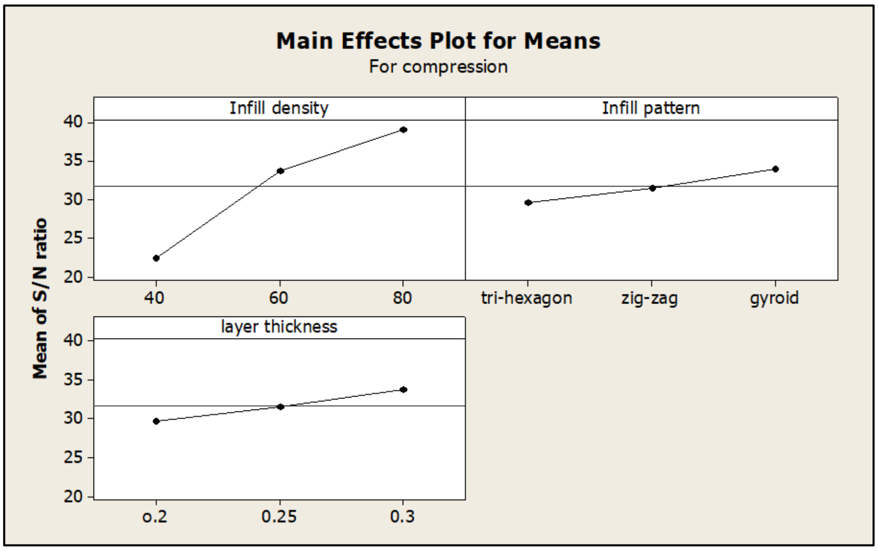

Figure 5: Experimental compression strength S/N ratio plot

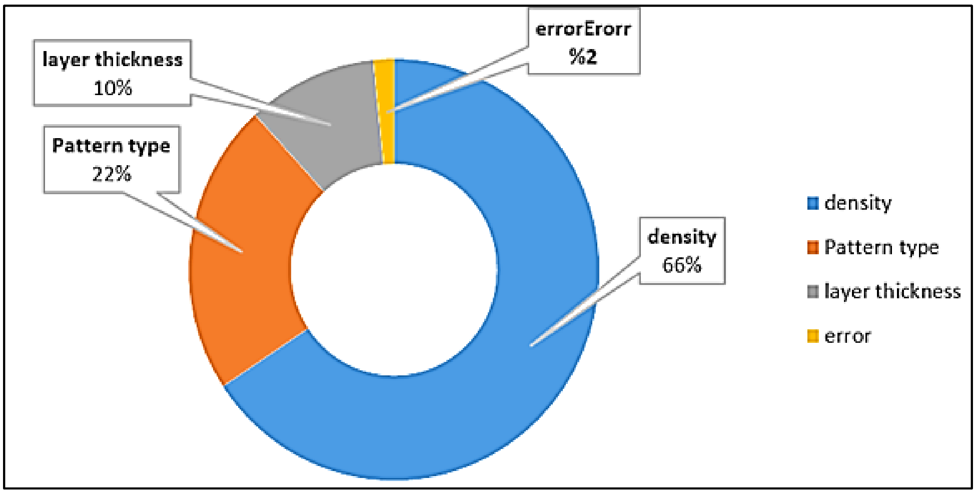

Figure 6: Process parameter percentages on tension strength

The regression method, which uses the Minitab package, was responsible for developing a statistical model of compressive strength, as shown in Equation 2. To forecast the compressive strength, this equation was used, and from it, the functions that would represent the predicted compressive strength were derived:

$$\text{Compressive strength} = -7.7 + 0.415\,(\text{infill density}) + 2.11\,(\text{infill pattern}) + 41.3\,(\text{layer thickness}) \quad (2)$$

According to research, mechanical qualities improve as infill density rises and decreases [16]. Layer thickness increases tensile strength. The layer thickness of (0.3 mm), infill density of (80%), and infill pattern of the Gyroid were best for tension strength as shown in Figure 7. Table 5 and 6 shows how much each element contributed to the answer (compressive strength) from the S/N ratio analysis of variance. Figure 8 shows that infill density contributed (60%), pattern (15%), and layer thickness (20%).

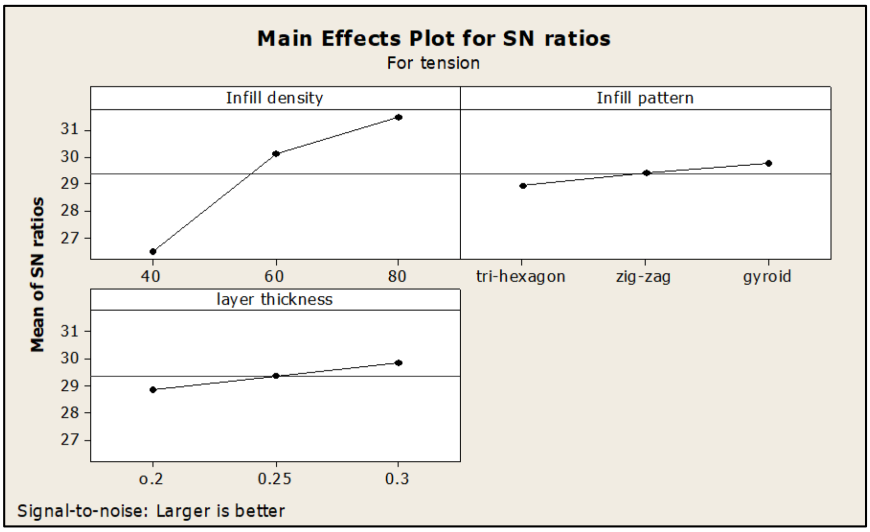

Figure 7: Experimental tension strength S/N ratio plot

Table 5: Signal-to-noise ratios for tension testing

Level	Infill density	Infill pattern	Layer thickness
1	21.16	28.74	28.27
2	32.51	30.55	30.89
3	37.82	32.20	32.33
Delta	16.67	3.46	4.05
Rank	1	3	2

Table 6: S/N ratio ANOVA for tension

Source of variance	DOF	Sum of squares	Variance	P (%)
density	2	344.2	172.1	60.74%
Pattern type	2	85.9	24.9	15.16%
layer thickness	2	116	58	20.47%
Error ,e	6	20.4		3.6%
Total	8	566.8		100

The regression method, which uses the Minitab package, was responsible for developing a statistical model of compressive strength, as shown in Equation 3. To forecast the tension strength, this equation was used, and from it, the functions that would represent the Prediction compressive strength were derived:

$$\text{Tension strength} = -8.1 + 0.417\,(\text{infill density}) + 1.73\,(\text{infill pattern}) + 40.5\,(\text{layer thickness}) \quad (3)$$

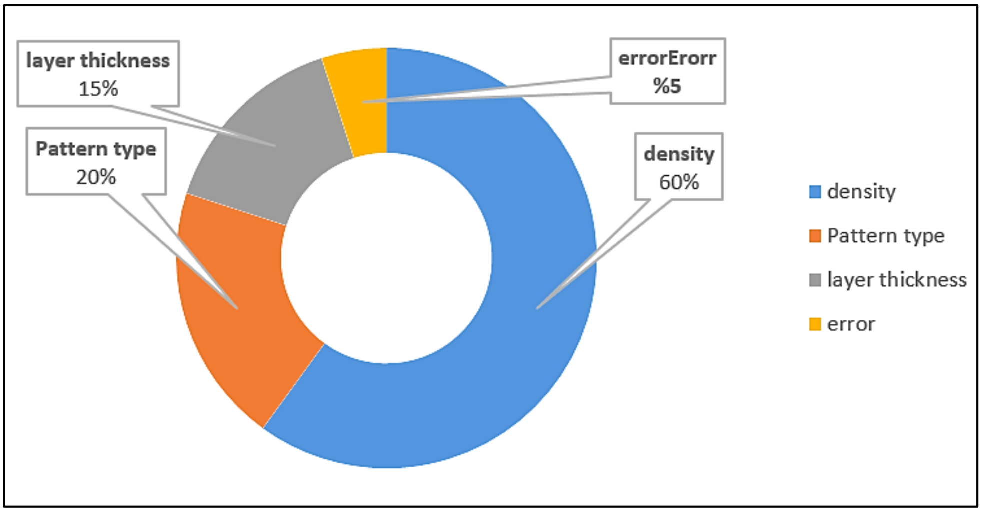

Figure 8: Process parameter percentages on compressive strength

Infill density refers to the amount of internal structure printed inside an object, which can significantly affect the mechanical properties of the final product; increasing the amount of material inside the printed object can improve its strength, stiffness, and resistance to deformation. By increasing the amount of material inside the object, a higher infill density might reduce load-induced deformation or collapse. When Higher infill density increases the object's weight, which strengthens it. [4,24].

Infill patterns describe a 3D-printed object's internal support system. The Infill pattern affects 3D-printed things' mechanical behavior under tension and compression. Infill patterns affect printed objects' stiffness, strength, and failure mode. FDM 3D printing uses tri-hexagon, zig-zag, and gyroid infill patterns. A gyroid infill pattern in FDM 3D printing provides a more effective internal support system that can distribute stress and strain more uniformly, reduce weight while maintaining strength, and enhance longevity. Sometimes, the gyroid infill pattern may be too complicated and time-consuming to print. Thus, the ideal infill pattern depends on the application and desired mechanical attributes, printing time, and material. A higher infill density can support the object's structure, decreasing load-induced deformation or collapse. A higher infill density may also raise the object's weight, improving its durability [3].

The layer thickness in FDM 3D printing affects the tension and compression mechanical **behavior** of 3D printed things. Due to layer bonding, larger layers make printed objects stronger and more durable. Thicker layers have more material and stronger connections when printing an object. This makes a product stronger, stiffer, and more stress-resistant. Additionally, thicker layers can reduce the printing time, which can be beneficial in applications where time is critical.

In tension and compression tests specifically, the layer thickness can affect the mechanical properties of the printed object such as its strength, stiffness, and failure mode. Thicker layers can result in an object that is more deformation-resistant and has a higher load-bearing capacity. In comparison, thinner layers may result in an object that is more prone to failure and has a lower load-bearing capacity. Agree with [4,24].to obtain a product with the best feasible strength parameters by filling the model to the greatest extent possible. That can reduce material consumption by adopting a particular filling structure of the printed components, which reduces part manufacturing time and costs of the printed element and the production process. As a result, 3D printing has become one of the industry's fastest-expanding segments.

Figures 9 and 10 show a bar chart comparing measured compression and tension strength values to regression model predictions can reveal model accuracy. The chart shows measured values as bars in red and prediction values as bars in blue. The bar chart shows the regression model average percentage error of 2.6437% prediction for compression. And an average percentage error of 2.7422% prediction for tension. Predicted values will be close to actual bars if they match measured values. To minimize the percentage error for prediction compression and tension strength, one must use a second or third-degree instead of linear regression, which needs to increase the number of experimental work.

A bar chart comparing measured compression strength values to anticipated values generated by a regression model can help decision-makers analyze the model's accuracy and effectiveness. It can also guide model improvement and research and development.

The maximum compression strength occurred at (80%) infill density, a Gyroid infill pattern, and (0.3) mm layer thickness for tension and compression; This may be caused by the greater use of polymer during printing, which results in a harder material and less free space within the printed product. As a result of the smaller pores and increased load-bearing capacity, the material becomes stronger. The material’s compressive strength is usually directly proportional to the infill ratio.

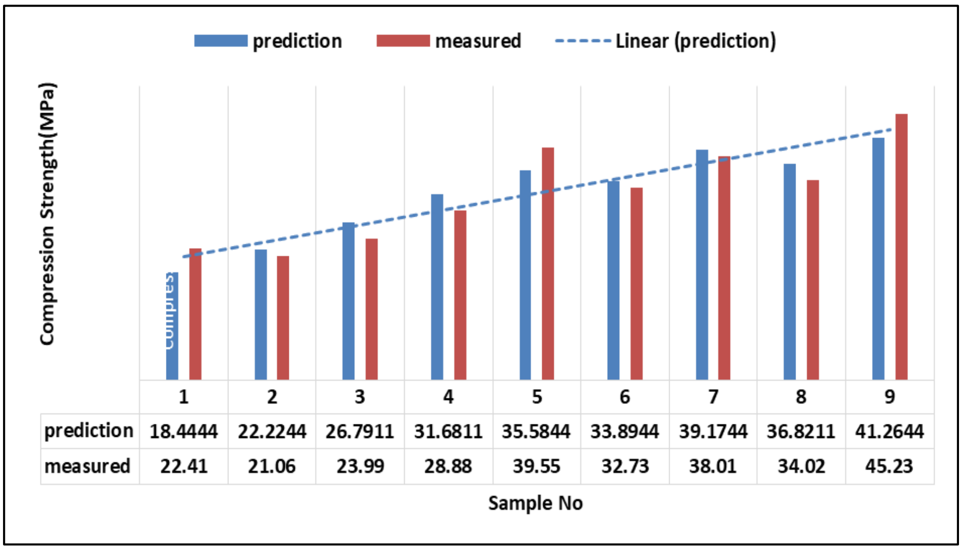

Figure 9: Bar chart of the compressive Vs Prediction Value

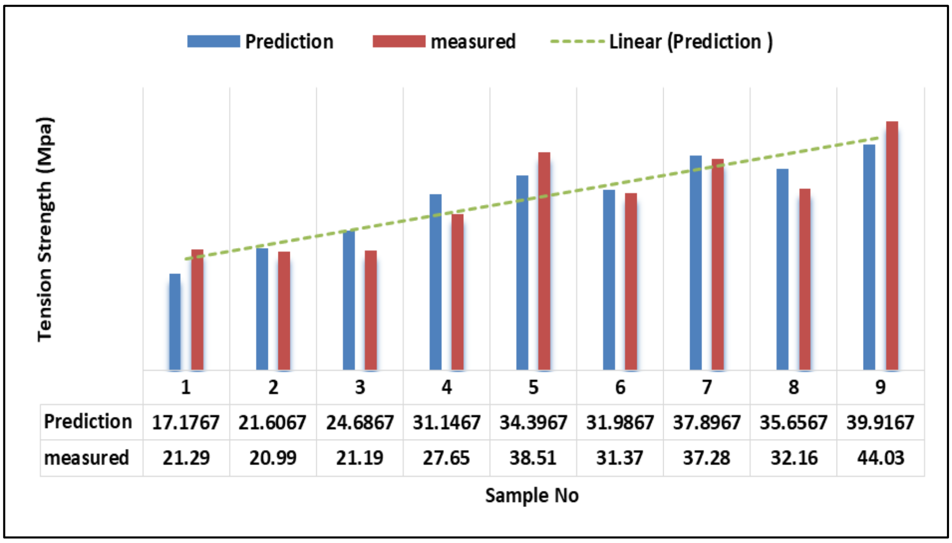

Figure 10: Bar chart of the tension strength Vs Prediction Value

Figure 11 displays the link between the anticipated and measured compressive strength values. This demonstrates that the efficiency response compressive strength approach uses a linear regression model to predict the values of the variables in Table 2. Display the probability drawing of the residual response for tension strength in Figure 12. A check on this plot reveals some interesting information.

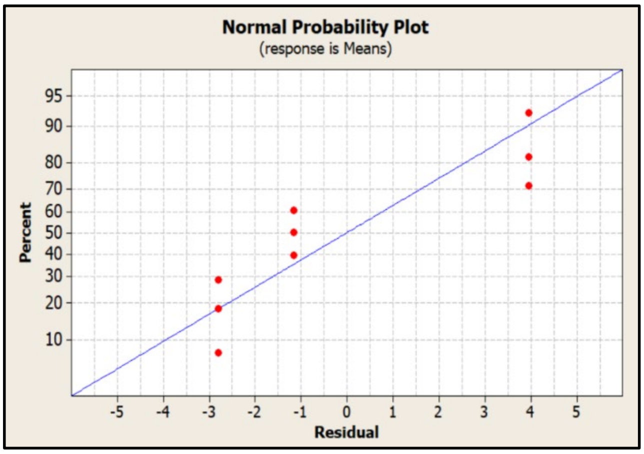

Figure 11: Probability of compressive strength

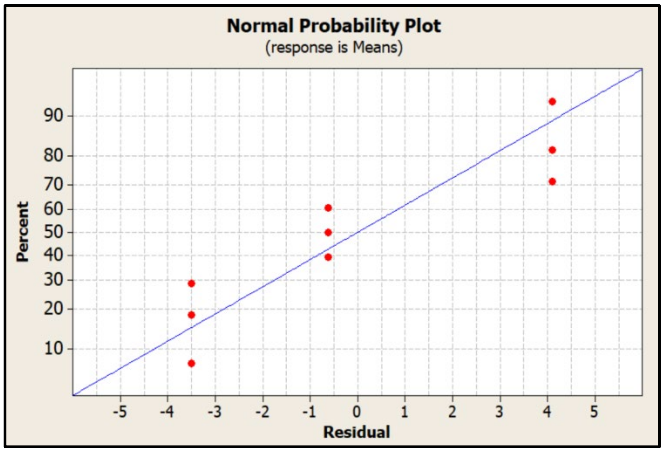

Figure 12: Probability of tension strength

4. Conclusions

The Taguchi approach was employed for design. PLA samples were printed with varying layer thickness, infill density, and infill pattern on a commercial FDM 3D printer.

- The findings demonstrated that anisotropic process parameters greatly impact 3D-printed products' mechanical qualities. Infill density dominates compressive strength (65%) because the fill with 80 % is like a solid part, so it has more strength effect than another parameter. But layer thickness has little influence (10%) on compression. Infill density dominates compressive strength with 60%, but infill pattern has little influence with 15% for tension.
- An object's infill density affects its strength and durability. Infill pattern, the interior structure's layout, can affect the final object's mechanical qualities. The Layer thickness affects surface polish and quality. The Taguchi technique recommended 80% infill density, a gyroid infill pattern, and 0.3 mm layer thickness for tension and compression. The linear regression model prediction equation correlates well with the measured value for compression strength with 97% accuracy. Measure the value for tension strength with accuracy (96%).
- Infill density, thickness, and pattern affect tensile and compression strength. As layer thickness decreases, several layers are needed, distorting influence decreases, and strength improves. Thus, experiment nine is the best 3D-printed structure for high-resistance applications. Maximum compression (45.23 MPa) and tensile strength (44.03 MPa).
- 3D printed PLA exhibits a non-symmetric tensile and compression behavior: under in-plane loading conditions, PLA seemed to be less stiff but more compressible.

Author contributions

Conceptualization, M. Abdullah and T. Abbas; methodology, M. Abdullah and T. Abbas; software, M. Abdullah and T. Abbas; validation, M. Abdullah and T. Abbas; formal analysis, M. Abdullah and T. Abbas; investigation, M. Abdullah and T. Abbas; resources, M. Abdullah and T. Abbas; data curation, M. Abdullah and T. Abbas; writing—original draft preparation, M. Abdullah and T. Abbas; writing—review and editing, M. Abdullah and T. Abbas; visualization, M. Abdullah; supervision, M. Abdullah and T. Abbas; project administration, M. Abdullah and T. Abbas. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

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

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