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A Statistical Investigation and Prediction of the Effect of FDM Variables on Flexural Stress of PLA Prints

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Keywords:

3D Printing; Bending Strength; FDM Process Variables; Linear Regression; PLA.

Highlights:

- *The flexural strength of the PLA printed part can be significantly increased by adjusting the basic parameters of the FDM process.*
- *The filler density is the main contributor to the flexural response.*
- *A linear fitted regression model for the three-point flexural strength has been developed and seems to adequately represent the responses.*

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Abstract: Due to its many engineering applications, low manufacturing costs, and environmental friendliness, 3D printing is considered one of the most promising manufacturing technologies. The quality of printed parts will inevitably be affected by the controllable variables used in the 3D printing process. The present study aims to investigate how different printing process parameters affect the bending strength of PLA prints. The ASTM D790 standard was used to fabricate the samples in this work, while the Taguchi principle was used to design the experiments. The following values were chosen: shell width (0.8, 1.2, 1.6, and 2 mm), layer thickness (0.15, 0.2, 0.25, and 0.3 mm), and infill density (40%, 60%, 80%, and 100%). The results showed that fill density is the most effective variable for improving bending strength. Measurements of infill density (100%), layer thickness (0.15 mm), and shell width (2 mm) gave the best results, which were calculated to be 83.1479 MPa in bending test. The mathematical model in this study was developed using linear regression analysis, and the residuals confirmed that the model fit the data well, with a maximum error of 6.1%.

التحقيق الإحصائي والتنبؤ بتأثير متغيرات FDM على إجهاد الانحناء لمطبوعات PLA

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الخلاصة
تعتبر الطباعة الثلاثية الأبعاد إحدى تقنيات التصنيع الواعدة نظرًا لتطبيقاتها الهندسية العديدة، وانخفاض تكاليف التصنيع، وملاءمتها للبيئة. حيث تتأثر جودة الأجزاء المطبوعة بالمتغيرات المستخدمة في عملية الطباعة الثلاثية الأبعاد. تهدف الدراسة الحالية إلى معرفة تأثير متغيرات عملية الطباعة المختلفة على قوة الانحناء لمطبوعات PLA. تم استخدام معيار ASTM D790 لتصنيع العينات في هذه الدراسة، بينما تم استخدام منهجية Taguchi لتصميم التجارب العملية. تم اختيار متغيرات العملية التالية: عرض الغلاف (٠,٨، ١,٢، ١,٦، و٢ ملم)، سمك الطبقة (٠,١٥، ٠,٢، ٠,٢٥، و٠,٣ ملم)، وكثافة الحشو (٤٠٪، ٦٠٪، ٨٠٪، و١٠٠٪). حيث أظهرت النتائج أن كثافة الحشو هي المتغير الأكثر فعالية لتحسين مقاومة الانحناء. أعطت نتائج كثافة الحشو (١٠٠٪) وسمك الطبقة (٠,١٥ ملم) وعرض الغلاف (٢ ملم) أفضل النتائج والتي تم مقاومة الانحناء لتكون (٨٣,١٤٧٩) ميجا باسكال في اختبار الانحناء عند قوة الانحناء ثلاثية النقاط. تم تطوير النموذج الرياضي في هذه الدراسة باستخدام تحليل الانحدار الخطي، وأكدت النتائج أن النموذج يطابق البيانات بشكل جيد بنسبة انحراف قصوى قدره ٦,١٪.

الكلمات الدالة: الطباعة ثلاثية الأبعاد؛ قوة الانحناء. متغيرات عملية FDM؛ الانحدارالخطي؛ جيش التحرير الشعبى الصينى.

1.INTRODUCTION

Computer-aided 3D modeling products can be rapidly prototyped with 3D printing [1]. Additionally, it enables an early and effective design process, which results in successful and effective end products [2]. When it comes to manufacturing techniques that save energy and materials, 3D printing is among the most significant [3]. Numerous industries could see changes in their manufacturing processes as a result of 3D printing technology [4, 5]. The capacity of 3D printing to decrease production time and material consumption has led to its rise in popularity in recent years [6]. It is possible to produce functional parts through the use of 3D printing technology [7]. The most popular approach is FDM [8]. The FDM procedure, depicted in Fig. 1, is based on the idea that plastic filament material is added layer by layer [9,10]. Based on previous studies and searches of the production technologies and filament materials, a few researchers have studied and analyzed the effect of different filling densities on tensile strength. Further research is necessary to develop the mechanical properties and quality of FDM-printed components. This study focuses on analyzing the effect of infill density on the flexural strength of FDM components compared to other factors. Gurcan et al. [11] proposed that PLA filament is preferred due to its suitability for recycling in comparison to other filaments once they become waste. This study supports the use of PLA filaments because they are biodegradable, made from sustainable resources, and can be printed at lower temperatures, which conserves energy. Researchers use the Taguchi method to analyze how much a product changes by controlling its attributes and features. To choose the ideal parameters, the experimental data are analyzed. Identifying the variables that have the biggest influence on the outcomes is also possible. [12-14]. According to the literature, the most effective strength characteristics of elements fabricated by the FDM process are the infill pattern, infill density, and layer height [15-18]. The average strength increases with each infill structure in direct proportion to the infill density. Operating at an infill density of 20% or less is inappropriate in applications with important effect values [19]. Three-point flexural strength test parts were printed with a linear pattern in this study, and infill densities of 40%, 60%, 80%, and 100%, layer heights of 0.15, 0.2, 0.25, and 0.3 mm, and shell widths of 0.8, 1.2, 1.6, and 2.0 mm were investigated. The Taguchi methodology was used to calculate the S/N ratio. To ascertain the mechanical properties of printed test samples related to flexural strength, the results of the three-point bending test and the influence of the control parameters were evaluated. The current study aims to analyze the effect of filling density on the flexural strength of polylactic acid compared with the effect of other factors.

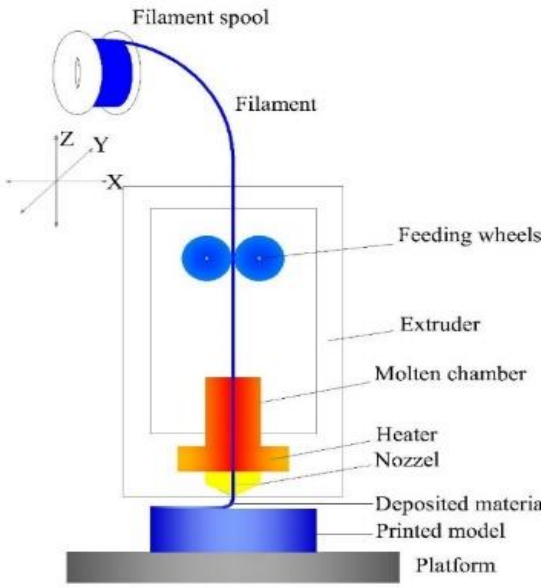

Fig. 1 Scheme of FDM Machine Developed by the Authors.

2. EXPERIMENTAL WORK

2.1. Flexural Strength Test

Product designers are frequently compelled to choose between composites and plastics. The suitability of a material for a given application is determined by several factors, including its flexural strength and modulus. ASTM D790 was used to validate bending strength, a measurement of a material's resistance to deformation under bending stress [20]. Materials with high bending strength indicate good-quality products [21].

2.2. Resources and Technique

ASTM D790 is commonly used to evaluate reinforced and unreinforced plastics, thermoplastics and thermosets, electrical insulation materials, and high-modulus composites [22]. 3.2 mm (thickness) 12.7 mm (width) 125 mm (length) plastic strip specimens are used in ASTM D790's test. The specimen is set up on two supports at a specific distance and is then pressed into the center with a point from top to bottom at a speed of 15 mm/min until it breaks or goes over a predetermined limit. The ASTM D790 3-Point Flexural Test Standards are depicted in Fig. 2 (all measurements are in millimeters).

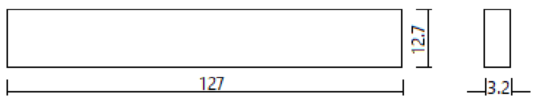

Fig. 2 ASTM D790-15 Standard Geometry for Three-Point Bending Test.

The Cura slicer program was used to convert the test parts from UGNX Computer-Aided Design (CAD) to G-code. The test samples were printed on an Ultimaker +2 with a 1.75mm PLA filament. The FDM system parameters and 3D printer properties are listed in Table 1.

Table 1 System Information and 3D Printer Specifications.

No.	System information	Specifications.
1	fabricating method	FDM
2	Bed size	223 x 223 x 205 mm
3	Machine size	342 x 493 x 588 mm
4	Diameter of the filament	1.75 mm
5	Type of the filament	PLA
6	Diameter of nozzle	0.4 mm
7	Nozzle temperature	205 C°
8	Bed temperature	65 C°
9	Printing speed	50 (mm/sec)
10	Machine type	Ultimaker +2
11	Slicer software	Cura
12	Design program	UGNX
13	Infill pattern	Line
14	Infill density	40, 60, 80, 100 (%)
15	Height of the layer	0.15, 0.2, 0.25, 0.3 mm
16	Shell width	0.8, 1.2, 1.6, 2.0 mm

2.3. Materials in the FDM Process

When the FDM technique first developed, there were only a few raw materials available; the two that were most widely used were polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) [11]. This was one of the main challenges this technology faced in its early stages. However, due to its advanced technological capabilities and low cost, numerous researchers have been inspired to find new raw materials, which has aided in its wide adoption and the development of previously unknown technology applications. Today, a variety of thermoplastic filaments are used in FDM printing, including nylon, ABS, PLA, PET-G (polyethylene terephthalate glycolized), TPU (thermoplastic polyurethane), PEEK (polyether-ether-ketone), and other composites. There are many different types of 3D printing materials, and each has different strengths and weaknesses. In addition to the functional aspects of different 3D printing materials, cost is also a very important factor for many product engineers. However, one of the most popular FDM thermoplastics is PLA, which is simple to use as a filament in an FDM-capable 3D printer [23]. The preference for PLA filaments for recycling over other types led to their selection for this study. Additionally, PLA is a biodegradable substance that can be printed at lower temperatures, which helps with energy conservation.

2.4. Design of Experiments

The Taguchi design of the experiment method is used to convert the objective values into a signal-to-noise S/N ratio [24]. Taguchi classified the factors as control factors or noise factors. Control factors are those chosen by the designer. Noise factors include other factors such as temperature and humidity. The Taguchi method employs signal-to-noise to improve system robustness and desensitize the process to noise factors. The signal-to-noise ratio (S/N) can be used to achieve the best quality design with the least amount of variation. It is especially useful for factor weighting and improving quality [25]. The Taguchi method was used to determine the proper levels of the various variables. Using L16, one of Taguchi's orthogonal matrices, experiments were planned and carried out. The results of the experiments were then analyzed to determine the proper levels of variables. Three variables with four levels each make up this L16 design. There are a total of 16 rows. Table 2 lists the variables and control levels for Taguchi L16 used in this study.

Table 2 The Factors and Control Levels for Taguchi L16.

No.	Factors	Sym.	unit	L1	L2	L3	L4
1	Infill (%)	A	(%)	40	60	80	100
2	Layer Height (mm)	B	mm	0.15	0.2	0.25	0.3
3	Shell width (mm)	C	mm	0.8	1.2	1.6	2.0

Based on the experimental design using the Taguchi concept, 16 samples were fabricated as shown in Fig. 3, according to the variables and levels shown in Table 3.

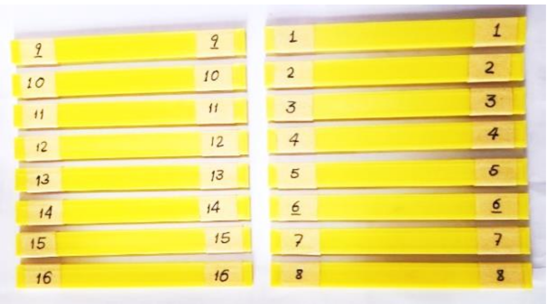

Fig. 3 Fabricated Samples for a Three-Point Flexural Strength Test.

Table 3 Design of the Experiments.

Sample	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	2
6	2	2	1
7	2	3	4
8	2	4	3
9	3	1	3
10	3	2	4
11	3	3	1
12	3	4	2
13	4	1	4
14	4	2	3
15	4	3	2
16	4	4	1

3.RESULTS

The purpose of this study is to improve the mechanical properties of PLA parts fabricated with variable infill density, variable layer height, and variable shell width. The flexural strength values for the mechanical tests listed in Table 4 were obtained as a result. In the "bigger is better" equation, the S/N ratio is used Eq. (1).

$$\frac{S}{N} = -10\ log\left[\frac{1}{n}\sum_{i=1}^{n}\quad\left(\frac{1}{y_i}\right)^2\right] \quad \textbf{(1)}$$

Where:

yi is the results of the experiments

n is the trial

Table 4 Taguchi Orthogonal Array Test Results.

Sample	A	B	C	Flexural stress (MPa)
1	1	1	1	61.4237
2	1	2	2	60.9603
3	1	3	3	59.8364
4	1	4	4	59.2897
5	2	1	2	66.8615
6	2	2	1	63.5376
7	2	3	4	60.8382
8	2	4	3	61.852
9	3	1	3	74.7676
10	3	2	4	72.6127
11	3	3	1	69.3029
12	3	4	2	65.6833
13	4	1	4	83.1479
14	4	2	3	77.3871
15	4	3	2	75.0778
16	4	4	1	68.7676

According to the experimental findings, specimen 13 demonstrated greater mechanical strength than the other specimens. Sample 13 produced better mechanical strength because it was printed with a maximum infill density of 100%, a minimum layer height of 0.15 mm, and a maximum shell width of 2 mm. For each fabricated sample, an accurate caliper was used to measure the dimensions, as shown in Fig. 4.

Fig. 4 Measurements of the Sample Dimensions.

In the three-point test method, the sample is set up on two supports at a specific distance from one another and is then pressed into the center with a point from top to bottom at a speed of 15 mm per minute until it breaks or goes beyond a predetermined limit.

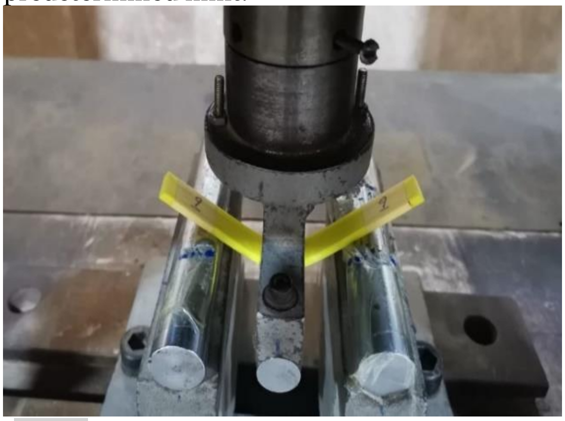

Fig. 5 Three-Point Flexural Test of a Sample.

A rectangular sample under a load in a three-point bending setup is illustrated in Fig. 6.

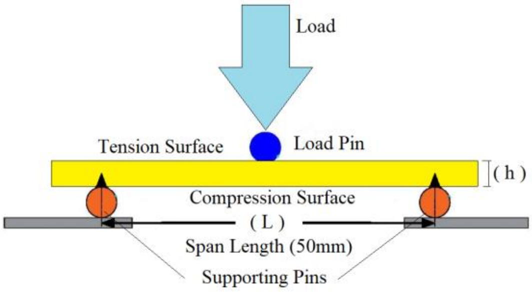

Fig. 6 Three-Point Bending Setup Developed by the Authors.

The test specimen's bending stress must typically be calculated to be less than 5% without the specimen breaking. Eq. (2).

$$\sigma = \frac{3PL}{2bh^2} \quad \textbf{(2)}$$

- P: is the fracture load (N)
- L: is the span length (50 mm)
- b: is the specimen width (12.7 mm)
- h: is the specimen thickness (3.2 mm)

Each response characteristic is converted into a response table by Minitab. Response charts can show which variable has the biggest influence on the response. The response values for three-point flexural strength are shown in Table 5.

Table 5 Response for Means.

Level	Infill Density (%)	Layer Height (mm)	Shell Width (mm)
1	60.83	71.55	65.76
2	63.77	68.62	67.15
3	70.59	66.76	68.46
4	76.10	63.90	69.47
Delta	15.72	7.65	3.71
Rank	1	2	2

The statistical analysis of the data in Table 4 shows that infill density (Rank 1) has the greatest impact, followed by layer height (Rank 2) and shell width (Rank 3). The main effect plot for bending strength is shown in Fig. 7. Table 6. shows the results of the analysis of variance (ANOVA) for the bending strength of PLA specimens. Factors Infill density (%) and layer height (mm) are significant factors for bending strength because their p-values are less than 0.05, while the shell width is not a significant factor due to its p-value being greater than 0.05. By dividing each input control factor's sum of squares by the sum of all squares, the percentage contribution of each factor was calculated. The last column of Table 4 lists the control factor percentage contribution values. The maximum contribution (77.6%) was found to come from the infill density, followed by layer height (16.3%) and shell width (4.1%), according to the ANOVA results.

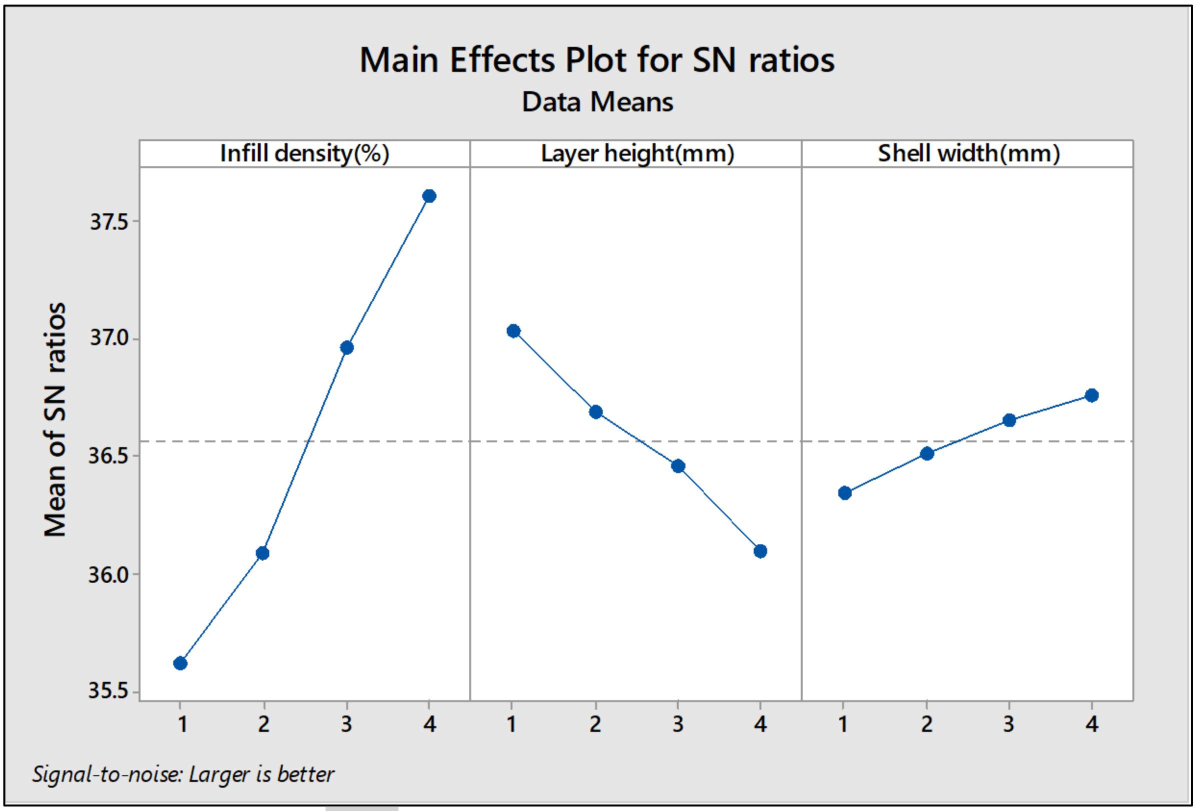

Fig. 7 Main Effects Plot for Bending Strength.

Table 6 Variance Analysis for Flexural Stress.

Source	DOF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Infill (%)	3	591.54	197.179	77.54	0.000	77.6 %
Layer Height (mm)	3	124.03	41.35	16.26	0.003	16.3 %
Shell Width (mm)	3	31.19	10.4	4.09	0.067	4.1 %
Error	6	15.26	2.543			2 %
total	15	762.02				

Observing the last column in Table 6. shows that there is an error percentage of (2%), and this can be attributed to the effect of some variables that were not taken into account in this study, like infill pattern, printing speed, printing temperature, nozzle diameter,..etc. The linear model of the flexural strength versus Infill density, Layer height, and Shell width regression Equation for PLA is shown in Eq. (3).

$$\begin{aligned} &Bending\ Strength\ (MPa) \\ &= 67.709 + 5.3966\ Infilldensity(\%) \\ &- 0.6204\ layer\ height(mm) \\ &+ 2.4928\ shell\ width(mm) \end{aligned} \quad \textbf{(3)}$$

The suitability of the developed model was assessed using the normal probability plot. Fig. 8 shows the residuals for bending strength in a normal probability plot. It is found that the residuals are relatively close to the normal probability line, supporting the suitability of the developed model. To determine whether the fitted regression model is appropriate for the samples' bending strength, the measured and predicted results were compared (Table 7).

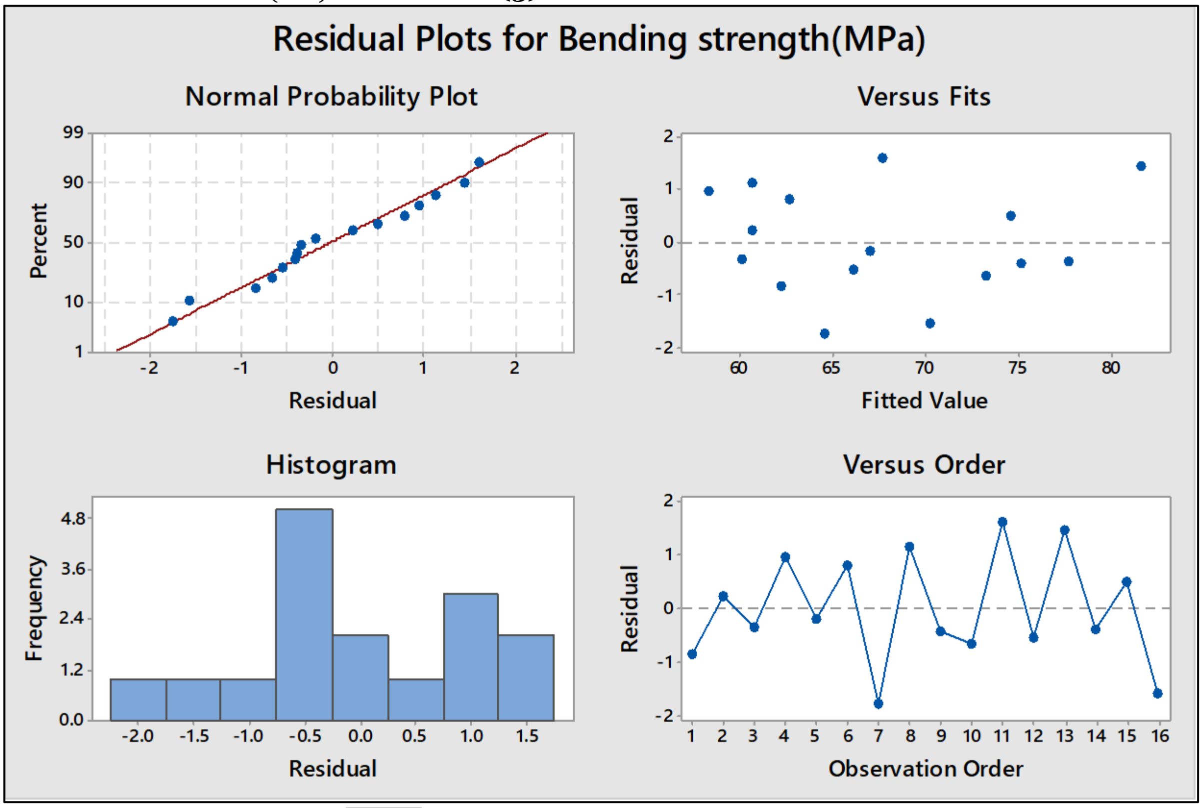

Fig. 8 Residual Plots for Flexural Strength.

Table 7 Experimental Results Versus Predicted Results.

Sample No.	A	B	C	Flexural strength (MPa) Measured	Flexural strength (MPa) Predicted	Error %
1	1	1	1	61.4237	62.2674	1.3
2	1	2	2	60.9603	60.7294	0.2
3	1	3	3	59.8364	60.1838	0.5
4	1	4	4	59.2897	61.1952	3.2
5	2	1	2	66.8615	67.0499	0.2
6	2	2	1	63.5376	62.7364	1.2
7	2	3	4	60.8382	64.5900	6.1
8	2	4	3	61.852	60.7130	1.8
9	3	1	3	74.7676	75.1843	0.5
10	3	2	4	72.6127	73.2699	0.9
11	3	3	1	69.3029	67.6951	2.3
12	3	4	2	65.6833	66.2172	0.8
13	4	1	4	83.1479	81.6991	1.7
14	4	2	3	77.3871	77.7620	0.5
15	4	3	2	75.0778	74.5864	0.7
16	4	4	1	68.7676	70.3329	2.3

Based on the results displayed in Table 6, the linear fitted regression model for the three-point flexural strength seem to adequately represent the responses with a maximum error of 6.1%. The infill density has an impact of 77.6 %, the layer height has an impact of 16.3%, and the shell width has an impact of 4.1 % on the three-point flexural strength values. ANOVA supported the findings of the three-point bending strength values. For PLA filament, the ideal values for the different process parameters are, in order, 100% infill density, 0.15 mm layer height, and 2 mm shell width.

The results showed unequivocally that the impact of the filling density is much higher than other factors on the flexural stress of printed parts, which reinforces the idea of the necessity of focusing and investing in this variable when designing prints in applications that are subject to bending.

4.CONCLUSION

The Mechanical characteristics of the FDM-fabricated PLA by varying the infill density, layer height, and shell width were examined, and the following conclusions were reached:

- ANOVA revealed that the infill density is the most significant factor that has a 77.6% contribution to the bending strength of PLA. Layer height has a 16.3% contribution to bending strength, while the shell width has a 4.1% contribution to bending strength.
- With the help of linear regression analysis, a mathematical model was developed, and residual plots demonstrated that it was suitable with a maximum error of 6.1%.
- The infill density is the main controlling factor that has an impact [77.6%] on the PLA's flexural strength, according to the overall results.
- Despite the influence of the shell width factor [4.1%] on the flexural stress, it cannot be considered to have a significant impact, compared to both the infill density and the layer height.
- Increasing the number of layers increases bending strength, and this can be achieved by choosing a relatively low layer height, as a layer height of 0.15 mm gives better flexural strength than other heights, as the thickness of the layer decreases, the number of layers increases accordingly.
- It is found that the best FDM control factor levels for PLA are 100% infill density, 0.15mm layer height, and 2mm shell width.

The results concluded in this research are consistent with the findings of previous research: [26-29]

5.FUTURE WORK

The outcomes of this study can be used as information for 3D printing setup parameters and as the foundation for additional research. It is advised that in future studies, the number of parameters is increased to obtain a more accurate result, as the current study was restricted to the investigation of only three process parameters.

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