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Research article

Optimizing FDM Parameters for Reliable and Efficient Production of Biomedical Parts

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A B S T R A C T

Additive manufacturing is a process of fabricating a 3D Parts in layer fashion using a computer created design. AM is a globally adopted technique, owing to parts part customization, fabricate complex geometrical shapes, create a light weight structures, more flexible, efficient, and sustainable approach to manufacturing compared to traditional methods. Among, the distinct AM process methods, the Fused Deposition Modeling or Fused Filament Fabrication has regularly popular among engineers/researchers/scientist that are working in the medical field (prosthetics, custom surgical models), manufacturing aids (jig, fixtures, tooling) etc. because to its cost effectiveness, wide range of material uses, relatively simple to use and print strong and durable parts then other AM process methods. Total 18 Polylactic Acid (PLA) material samples, 9 for the tensile strength test and 9 for the 3-point bending test were fabricated using an FDM 3D printer using distinct fixed and variable combination of parameters in the current investigation. The universal testing machine (UTM) was used to test the 3D printed samples for tensile and 3-point bending strength. Finally, the Signal-to-Noise ratio (S/N) Analysis of Variance (ANOVA) was used to choose the best possible combinations of the parameters. The findings demonstrated that the greatest tensile strength (21.85 MPa) was achieved at optimal settings when the raster angle was 45º, the printing speed was 50 mm/sec, and the layer height was 0.50 mm. Similarly, the maximum bending strength was achieved at optimal parameters when the raster angle was 90º, the printing speed was 50 mm/sec, and the layer height was 0.15 mm.

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1. INTRODUCTION

Additive manufacturing (AM) is a process of creating 3D components using digital CAD model by material addition in layer fashion. Additive manufacturing has a number of merits over traditional manufacturing methods such as ability to fabricate complex shapes, flexibility in design, ability to create light weight parts with internal structure, fast design and production, environmental friendly, minimizing waste, cost effective and part customization, very less human intervention etc. [1-5]. Thus 3D printing gained popularity in different sectors such as aerospace, medical, automotive, military, food industry, dental, customer goods and other associated sectors [6-9]. But recently, AM is used to fabricate biomedical implants, organ printing and scaffolds. However, the use of additive manufacturing in biomedicine is still in its early stages, but the potential is vast. [10]. There are distinct 3D printing methods such as stereo lithography, fused filament fabrication (FFF), binder jetting (BJ), sheet lamination (SL), etc. Thus each printing methods have own merits and demerits, and are chosen based on requirements of printer cost, product quality and mechanical strength required. By all above all these printing methods, FDM is becoming more and more well-liked among academics, the aerospace and medical sectors, etc., because of many key advantages such as FDM printer and filament are generally the most cost affordable, uses wide range of materials (PLA, ABS, nylon, & metal filled filaments), user friendly, faster printing speed as compared to SLA, easy to use, ability to fabricate custom objects, mainly for orthopedic use etc. [11-14]. In terms of the healthcare industry, medications and medical equipment of the future will be tailored for individual individuals, taking advantage of AM characteristics to image people and identify appropriate devices [15]. The literature claims that FDM is the only technique utilized to create customized catheters that show promise [16]. FDM has the potential to be used in the production of prosthetics, implants, orthoses, and surgical equipment [17]. As a result, components with greater dimensional stability that are neat and reasonably priced have been produced using FDM printing.

In addition, FDM) uses many distinct materials named as ABS, PLA, PC, Polyetheretherketone (PEEK), Polycarbonate (PC), Nylon, Thermoplastic polyurethane (TPU), metal filled filaments and distinct blends for different applications that comprise quick prototyping, automotive, biomedical, toys, aerospace, medical, and sports, as well as sophisticated composite parts. However, out of all of these above materials, PLA is strongly advised for use in medical due to a number of its characteristics, including low melting point, biocompatibility, eco-friendliness in material handling and processing, colorlessness, ease to print, and bendability [18–21].Comparing injection-molded polylactic acid with polylactic acid created by 3D printing, Song et al. 2017 [22] shown that the latter displays worse mechanical characteristics. AM polymer implants providing exciting possibilities, but there are still limitations such as less mechanical properties in the implants owing to different factors (uneven layering, microscopic voids etc.), since 3D printed implants are relatively new technology, there are limited data on how they hold up in the body over long period, not all polymers are equally biocompatible, meaning the body might reject them or they could cause inflammation. Nonetheless, by using an appropriate coating on polymer implants, these qualities can be enhanced [22, 23].

Che et al. [24] declared that metal powders on polymer were feasible. Using a thermal spray technique, 3 distinct powders material i.e.—tin, copper, and iron—were effectively deposited on 5 different samples using cold spray. On the Al substrate, Sova et al. [25] applied a 316 L coating using the thermal spray process, often known as cold spraying. The porosity of the cold spray coating is mostly influenced by the granulometry of the 316L powder, according to the results. In addition, the laser post-treatment primarily strengthens the coated samples' resistance. PLA samples were created using an FDM printer by R. Kumar et al. [26], and then 316L stainless steel was applied to the samples. Tensile and flexural strength tests were completed last. The findings indicated that the greatest tensile strength (29.51MPa) & bending strength (98MPa) were attained at the optimal parameters, which were raster angle of 30º, no. of top & bottom layer 3, and thickness of coating is 100μm. Additionally, a number of authors

examined how the properties of thermoplastic material were affected by the FDM parameters (layer height, raster angle, infill pattern, printing temperature, printing speed, number of contours, filament diameter, layer orientation, infill density, build plate temperature, nozzle diameter, etc.). By using the FDM technique, a variety of PLA components' characteristics have been examined through mechanical testing. Further based upon literature of various researchers printing parameters were selected in the current investigation [27-35]. Garg et al. [36] Lower raster angles resulted in greater values of flexural strength. The reason for this might be that at a lesser raster angle, the layer exhibits resistance to bending. The literature analysis also indicates that because metal implants have strong mechanical qualities, numerous researchers have used them. But, implants that are made of metal have some limitations (higher cost of machining/forming), heavy weight, wear resistance etc. To overcome this issue, in the current era the various researchers used thermoplastic polymer [37-38]. Hence, this study explores the effect printing parameters for especially for biomedical use (little finger systems).

Research Questions

(i) What effect do AM parameters have together?

(ii) Why FDM is considered as better printing technique compare to other?

Hence, the current study aims to determine the impact of fused deposition modelling (FDM) settings on the tensile & bending properties of PLA samples that are 3D printed. Therefore, the inexpensive PLA material samples may be used in various biomedical use, including small finger devices.

2. MATERIAL AND METHOD

The current study comprises: (i) Selection of light weight biocompatible Polymer material (ii) Choosen of cost effective printer (iii) Selection of printing parameters (iv) Printing of parts as per selected parameters for tensile and bending testing (v) Parameter optimization using Taguchi's L-9 orthogonal array (vi) recommended the ideal set of variables and outcomes.

2.1. Material Selection

The material of biocompatible type used as a filament in this current research was PLA PRO+ (Polylactic Acid) having 1.75 mm diameter. PLA has a property to print easily, it doesn't warp easily and lesser temperature of filament. The PLA material was procured from “WOL 3D India Ltd”. Polylactic Acid is the good choices for FDM 3D printer because of its several attractive properties such as lower melting point compared to other filaments, making it easier and safe to use, and generally considered non-toxic. In the recent days, this material is using in many field of use such as medical (suture, implants, drug delivery system), agriculture (mulch films & slow release fertilizer containers), textile (sportswear, home furnishings), packaging (food containers, cutlery), dental, domestic etc. [39]. The key characteristics (mechanical and physical) of raw PLA represented in Table 1.

Table 1. Physical & mechanical characteristics of the PLA material.

Properties	Values
Melting -temperature	130 to 180°C
Young's modulus	2.7-16 GPa
Rockwell hardness	88 HR
Density	0.00105 kg/mm^3
Tensile strength	59 MPa (Max)
Elongation during a break	7%
Flexural strength	108 MPa

2.2. Equipment & Printing Parameters used for the Preparation of PLA Samples

The FDM/FFF printer (K1 Series3D Printer Filament Slice Parameters) having dimensions 435 x 462 x 526 mm was used with Creality Print Software to fabricate PLA samples. A total of eighteen samples were created using a low-cost FDM printer for the tensile test (dog bone form) in accordance with ASTM D638 and the three-point bending test (rectangular shape) in accordance with ASTM D695. These samples were used for bending & tensile strength analysis. On the other hand, an FDM printer was utilized to fabricate test samples using fixed as well as variable settings. The variable & fixed parameters were chosen after an extensive literature study of various researchers [40-41] represented in Table 2 & Table 3.

Table 2. Variable settings that the FDM printer uses to create a samples.

Sample Order	Raster Angle (°)	Printing Speed in mm/sec.	Layer Height in mm
1	0	10	0.50
2	0	30	0.15
3	0	50	0.25
4	45	10	0.15
5	45	30	0.25
6	45	50	0.50
7	90	10	0.25
8	90	30	0.50
9	90	50	0.15

Table 3. Set settings that are applied while creating PLA samples.

Parameter	Value
Diameter of nozzle	0.2 mm
Type of Orientation	Flat
Infill density	100%
Pattern (Infill)	Triangular
Top/bottom thickness	0.8 mm
Printing temperature	230°C
Temperature of Build plate	45°C
Diameter of Filament	1.75mm

The image of 09 samples manufactured by the FFF printer for tensile and 3-point bending test are represent in Fig. 1 (a) & (b).

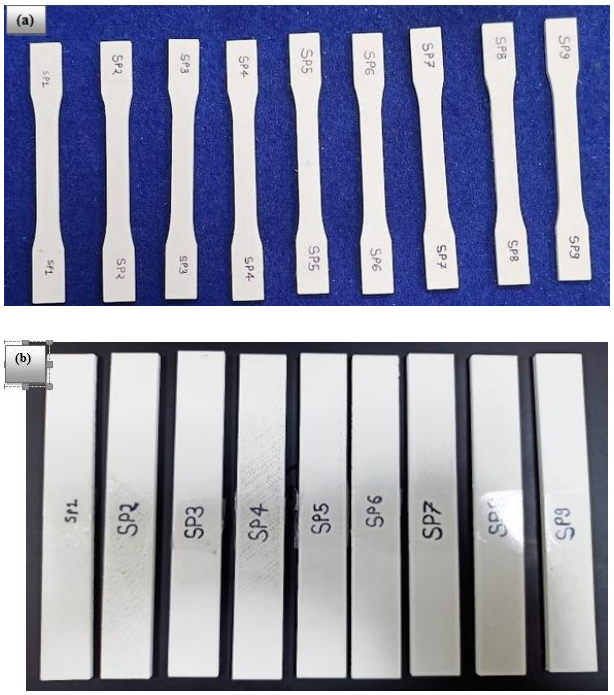


Fig. 1. PLA printed samples images by FFF printer (a) tensile test (b) r 3 Point bending.

2.3. Mechanical Testing of PLA Samples

2.3.1. Tensile Testing

A UTM machine, was used to conduct a tensile test on PLA samples created using an FDM printer. Fig. 2 and 3 depict, respectively, the dimensions of the tensile test specimens & the machine configuration during tensile testing. Samples are developed in Solid works CAD software in accordance with established procedures for this experimental study, and a 3D model in STL format was made for Slicer Cura.

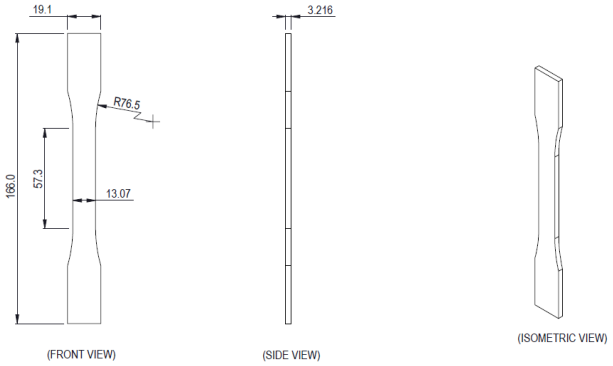


Fig. 2. Size of the tensile testing sample as per ASTM D638 designed in solid works.



Fig. 3. Actual image of universal testing machine (UTM) setup during tensile testing.

The maximum speed of the UTM (tensile test) machine, was 5mm/min. Furthermore, at room temperature, the Ínstron Blue Hill Universal Software was utilized to compute the tensile of test samples by recording data on a PC linked to the tester. Fig. 4 displays the real picture of the PLA samples following tensile testing.

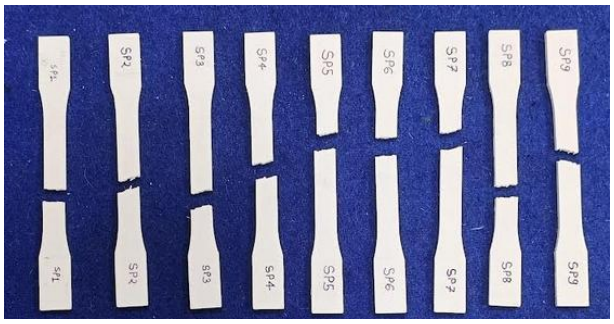


Fig. 4. The image of PLA samples after tensile testing .

2.3.2 Bending testing

The purpose of the 3-point bending test is to determine how a material will behave linearly when a force is applied vertically to its surface plane. As part of the bending test, the amount of deflection caused by the force application is calculated. The sample sizes were measured before the test. Next, in accordance with the ASTM D790 standard, the 3-point bend test was carried out on a UTM (INSTRON), as seen in Fig. 5(a). The UTM machine's maximum capacity was 10000N, and the test speed was 300 mm/min. Additionally, the flexural strength of test materials was calculated using the Intron Blue Hill Universal Software at room temperature, where data is captured via a PC linked to the tester. The samples' real appearance following the bending test is displayed in Fig. 5(b).

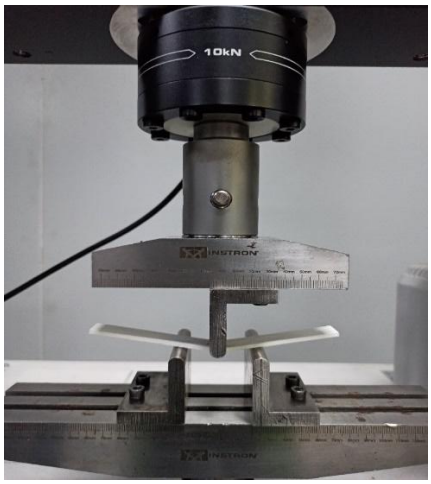


Fig. 5 (a). Actual image of universal testing machine (UTM) setup during 3-point bending test.

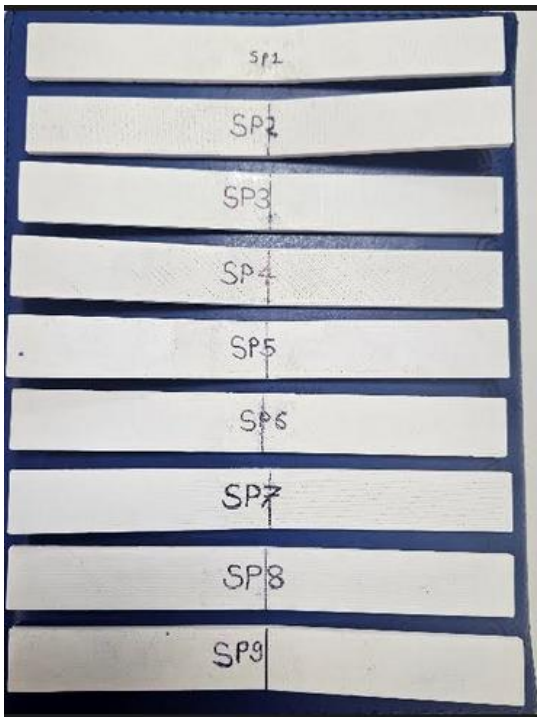


Fig. 5 (b). Actual image of samples after 3-point bending test.

3. DESIGN OF EXPERIMENT

The AM printed sample characteristic are majorly affected by the use of processing parameters to print the part. Hence, in the current investigation, three variable parameters i.e. raster angle in degree, printing speed in mm/sec. and layers height in mm were utilized to investigate their consequences on the flexural & bending characteristics of test samples. Different 3D printing parameters as well as levels utilized are represented in Table 4.

Table 4. Process variables along with level.

Parameter	Symbols	Level		
		1	2	3
Raster angle (°)	A	0	45	90
Printing speed (mm/sec.)	B	10	30	50
Height of layer in mm	C	0.15	0.25	0.50

The researchers' literature reviews [42–44] served as the basis for selecting the aforementioned 3D printing process parameters and their level. Moreover, the trials were configured as shown in Table 5 using Minitab software and "Taguchi's orthogonal array of fractional factorial design" (L9).

Table 5. Parameter combination ("Taguchi orthogonal array L9").

Run	Raster angle (A)	Printing speed (mm/sec) (B)	Layer height (mm) (C)
1	0	10	0.50
2	0	30	0.15
3	0	50	0.25
4	45	10	0.15
5	45	30	0.25
6	45	50	0.50
7	90	10	0.25
8	90	30	0.50
9	90	50	0.15

The printing parameters are represented by A, B, and C here; Layer height in millimeters, printing speed in millimeters per second, raster angle in degrees, and B and C.

4. RESULTS & DISCUSSION

4.1. Parameters optimization (tensile test)

The 'larger is better' S/N ratio equation is applied since the tensile strength in case of PLA-manufactured specimens must have a substantial value. Table 6 displays the S/N ratio and tensile strength test results.

Table 6. Tensile test outcomes.

Run	Raster angle (A)	Printing speed (mm/sec) (B)	Layer height (mm) (C)	Tensile strength (MPa)	SNRA1
1	0	10	0.50	16.91	24.5629
2	0	30	0.15	11.38	21.1228
3	0	50	0.25	15.56	23.8402
4	45	10	0.15	14.38	23.1552
5	45	30	0.25	16.41	24.3022
6	45	50	0.50	21.85	26.7890
7	90	10	0.25	16.44	24.3180
8	90	30	0.50	20.43	26.2054
9	90	50	0.15	13.73	22.7534

The sixth run yielded the highest tensile strength result of 21.85 MPa, while the second run produced the lowest tensile strength value of 11.38 MPa. Fig. 6(a) and 6(b) display the stress Vs. strain curve and the bar graph of the tensile strength of the tensile test samples, respectively.

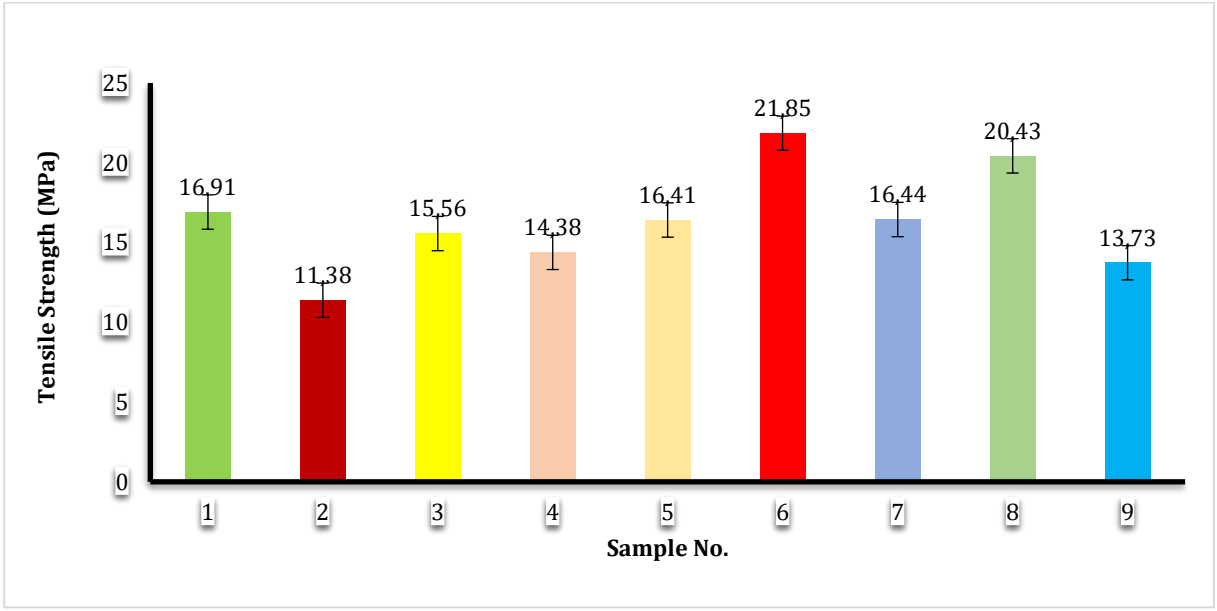


Fig. 6 (a). Tensile strength of test samples.

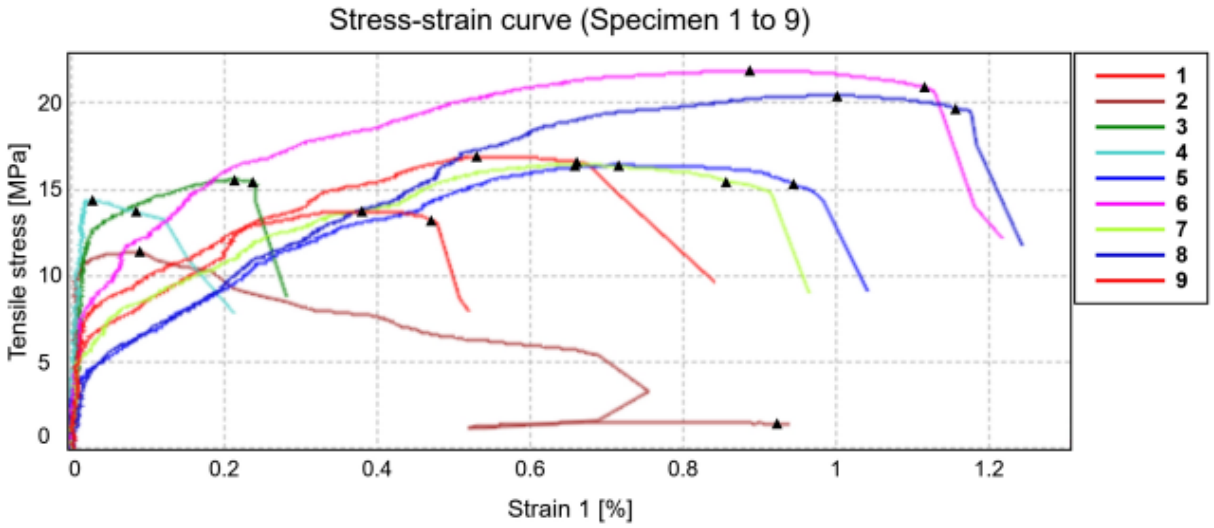


Fig. 6 (b). Stress Vs Strain graph for tensile testing.

Furthermore, Tables 7 and 8, respectively, display the response tables for the SN Ratio and the mean.

Table 7. Response Table (for S/N Ratios). Larger is better

Level	Raster angle in degree (A)	Printing speed (mm/sec) (B)	Layer height (mm) (C)
1	23.18	24.01	22.34
2	24.75	23.88	24.15
3	24.43	24.46	25.85
Delta	1.57	0.58	3.51
Ranking	2	3	1

Table 8. Response Table (for the determination of Means).

Level	Raster angle in degree (A)	Printing speed (mm/sec) (B)	Layer height (mm) (C)
1	14.62	15.91	13.16
2	17.55	16.07	16.14
3	16.87	17.05	19.73
Delta	2.93	1.14	6.57
Ranking	2	3	1

To maximize the tensile strength, the greatest S/N ratio for each factor must be chosen in order to find the ideal values. In addition, Figures 7 and 8, respectively, provide the major consequence, plot for the mean and SN ratio.

The English letter A2 indicates the “raster angle” when the ideal value is 45°, B3 indicates the printing speed when the ideal value is 50mm/sec, and C3 represents the layer height when the ideal value is 0.50mm in the event of a tensile test. This is the meaning of the optimal set of parameters, "A2B3C3." Additionally, the “SN ratio of tensile strength” is analyzed using ANOVA, as shown in Table 9 below.

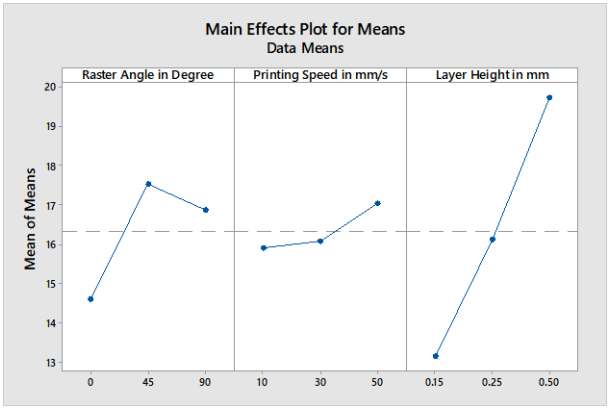


Fig. 7. Using Minitab software to plot the mean of the main impacts for raster angle, printing speed, and layer height.

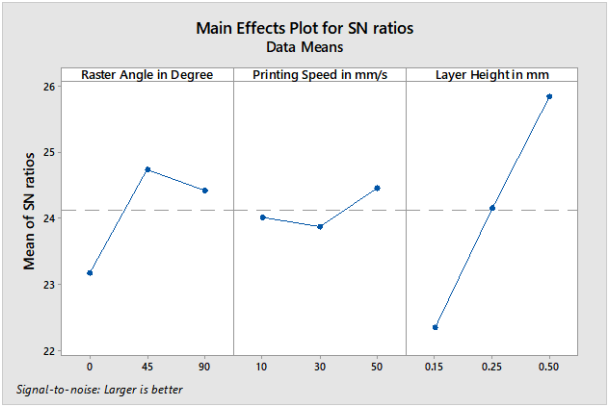


Fig. 8. Using Minitab software to plot the main effects of raster angle, printing speed, and layer height on the SN ratio. Hence, according to the diagram the optimum set of parameters are A2B3C3.

Table 9. Analysis of Variance (AOV) for Tensile Strength SN Ratio.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% contribution
Raster angle in degree	2	4.1436	2.0718	9.76	0.093	17.557
Printing speed (mm/sec)	2	0.5609	0.2805	1.32	0.431	2.376
Layer height (mm)	2	18.4717	9.2358	43.52	0.022	78.2679
Error	2	0.4244	0.2122			1.7982
Total	8	23.6006				100

Table 10. Tensile strength at optimal combination of process parameters.

Parameters	Best Contribution Sequence	Best Parameter Notation	Best Parameters Value	Max. tensile strength
Raster angle (degree)	2	A2	45	21.85 MPa
Printing speed (mm/sec)	3	B3	50	
Layer height (mm)	1	C3	0.50	

After applying these parameters, the layer height (mm) was found to be significant as the p-value is less than 0.05, which have maximum contribution i.e. 78.26%. However, the parameters of raster angle in degree & layers height (mm) have less contribution i.e. 17.55% and 2.37% respectively.

4.2. Process parameter optimization for the flexural test

The 'larger is better' S/N ratio calculation is applied because a flexural test requires a large number for the flexural strength.

Bigger is the better

$$SN_L = -10Log$$

"The flexural strength along with S/N ratio data are shown in Table 11 and in the study, n = 1 since the Avg. of the three tests is used to account for all runs".

Table 11. Flexural testing outcomes.

Run	Raster angle (degree) (A)	Printing speed (mm/sec) (B)	Layer height (mm) (C)	Bending strength (MPa)	SNRA1
1	0	10	0.50	14.70	23.3463
2	0	30	0.15	11.14	20.9377
3	0	50	0.25	17.80	25.0084
4	45	10	0.15	15.25	23.6654
5	45	30	0.25	18.14	25.1727
6	45	50	0.50	26.43	28.4419
7	90	10	0.25	21.57	26.6770
8	90	30	0.50	24.01	27.6078
9	90	50	0.15	17.19	24.7055

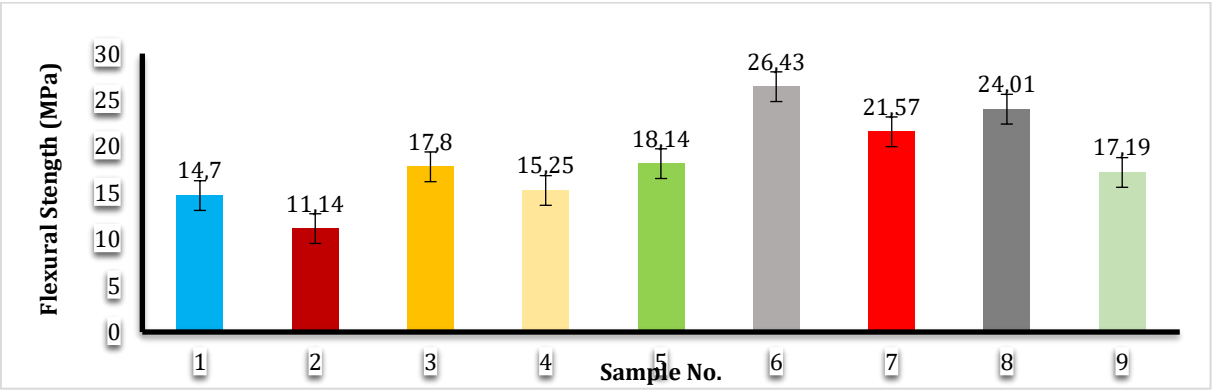


Figure 9 (a). Test sample flexural strength

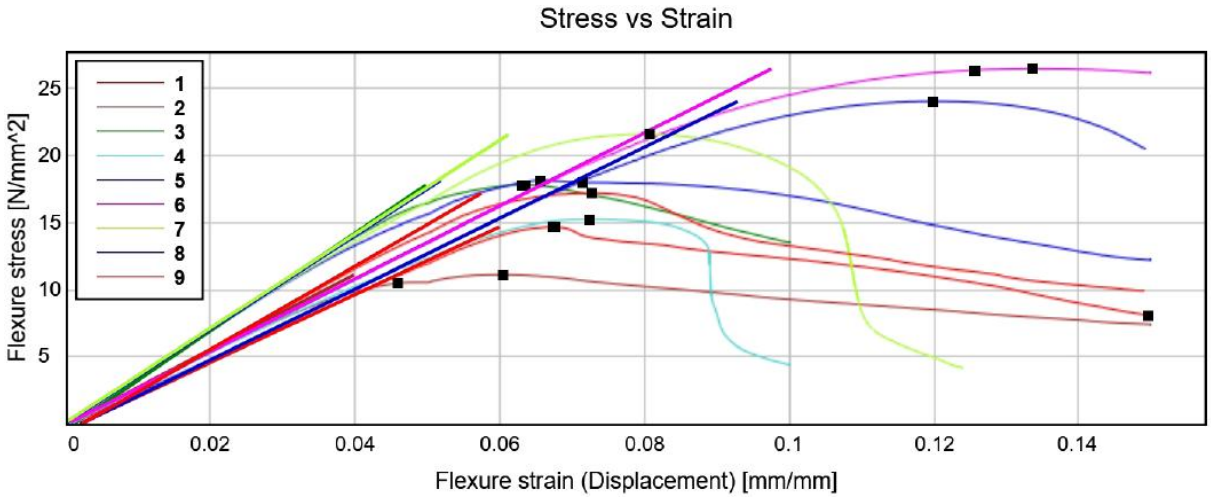


Figure 9 (b). Stress Vs strain curve for 3-point bending test

The sixth run produced the highest flexural strength of 26.43 MPa, whereas the second run produced the lowest flexural strength of 11.14 MPa. Fig. 9(a) and (b) display the bar graphs for the stress strain curve and 3-point bending strength of the test samples, respectively.

Furthermore, Tables 12 and 13, respectively, display the response tables for the mean and signal-to-noise ratio.

Table 12. Table of responses for means.

Level	Raster angle (degree)	Printing speed in mm/sec.	Layer height in mm
1	14.55	17.17	21.71
2	19.94	17.76	14.53
3	20.92	20.47	19.17
Delta	6.38	3.30	7.19
Rank	2	3	1

Table 13. Response Table (for S/N ratio)
Larger is better.

Level	Raster angle	Printing speed in mm/sec.	Layer height in mm
1	23.10	24.56	26.47
2	25.76	24.57	23.10
3	26.33	26.05	25.62
Delta	3.23	1.49	3.36
Rank	2	3	1

Nonetheless, choosing the largest (S/N ratio for each factor)—for which is chosen to boost bending strength—indicates the best (optimal) values. Furthermore, Fig. 10 and 11 provide the main effects plot for the SN ratio and the major effects for the mean.

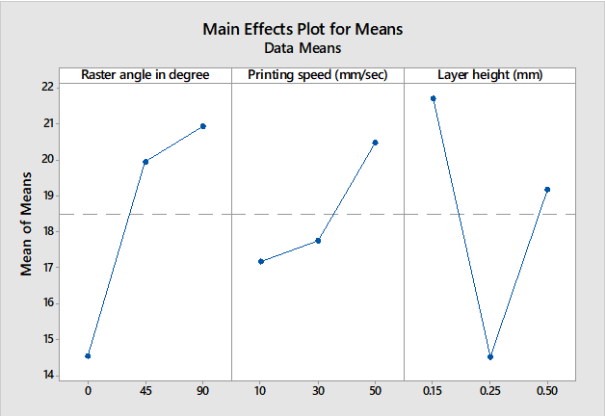


Fig. 10. Principal impact diagram for average: (a) for raster angle (b) Printing speed (c) Layer height.

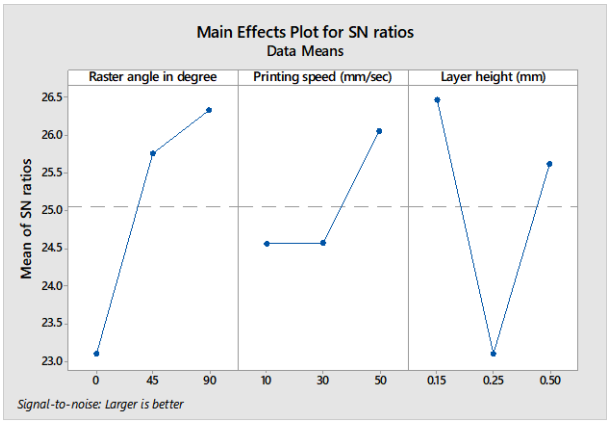


Fig. 11. Principal impact diagram for SN ratio: (a) Raster angle (b).Printing speed (c). Layer height.

Therefore, A3B3C1 is the ideal collection of parameters based on the graph.

Where the ideal combination of A3B3C1's properties is: When the ideal value is 90°, the raster angle is represented by the English character A3, B3 denote the printing speed

when the optimum value is 50mm/sec. and C1 represent the layer height when the value is 0.15mm in case of 3-point bending test.

In addition, the results of the ANOVA analysis of the mean 3-point bending strength's SN ratio are presented in Table 14.

Table 14. Study of variance of S/N ratio (for bending strength).

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% contribution
Raster Angle	2	17.864	8.9320	9.23	0.098	41.973
printing speed in mm/sec	2	4.405	2.2027	2.28	0.305	10.350
Layer height in mm	2	18.355	9.1775	9.48	0.095	43.1273
Error	2	1.935	0.9676			4.5465
Total	8	42.560				100

Table 15. Bending strength at the best possible process parameter combination.

Process parameters	Best Contribution Sequence	Best Parameter Notation	Best Parameters Value	Max. Bending strength
Raster angle (degree)	2	A3	90	26.43 MPa
Printing speed in mm/sec.	3	B3	50	
Layer height in mm	1	C1	0.15	

In case of bending test, among all the three parameters, the layer height was observed to be significant contribution i.e. 43.12%. However, the Raster Angle and printing speed have the contribution of 41.97% and 10.37% respectively. Therefore, Table 15 displays the ideal set of process parameters for 3-point bending strength.

5. CONCLUSIONS

In the current investigation, to analyses the consequence of AM printing parameters, the tensile & three-point bending strength of PLA material samples after fabrication using fused deposition modeling printer was determined experimentally by using fixed and variable process parameters. Observational data led to the following findings being made;

1. According to ANOVA results, which account for 78.26% of the total strength, layer height is one of the most important factors influencing tensile strength. On the other hand, approximate contributions to optimum response values from the raster angle and printing speed are 17.55% and 2.37%, respectively.
2. The raster angle, which accounts for 41.97% of the overall strength in the 3-point bending test, is one of the most important parameters influencing bending strength, according to ANOVA data. On the other hand, printing speed and layer height account for around 10.35% and 43.12% of the total, respectively.
3. The greatest 3-point bending strength (26.43 MPa) and maximum tensile strength (21.85 MPa) were found at the ideal combination at A2B3C3.

Future Scope: The bio glass coating help to improve the mechanical properties of 3D printed scaffolds will be added in the future study.

In addition, further to enhance the mechanical strength the 316L stainless steel material coating on PLA material using cold gas dynamic spray will be added in the future study.

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