Parameteric Optimization of Tensile strength and flexural strength in 3-D Printed components

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***Abstract*: *Additive manufacturing the most widely and commonly used technologies of manufacturing. One of the methods of additive manufacturing is Fused Deposition Modelling (FDM). FDM printed parts are being used in various application nowadays such as Aircraft parts, Automobile parts and many more. In every application, these parts have to undergo various mechanical stresses such tension, compression and flexural, etc., strength of these parts majorly depends on the various input parameters using which these parts are printed. So here we have selected some of the parameters which can have impact on the tension and flexural strength of the parts. To study the impact, we selected three parameters which are Layer Thickness, Infill Density, Feed rate and we used the material Polylactic Acid (PLA) to print the parts. Further using Taguchi's L9 algorithm we developed a DOE of Nine experiments which included various combination of those parameters, through that DOE parts were printed for both tension and Flexural strength test. Later with using those parts we performed two tests respectively for both Tension and Flexural Strength. Universal testing Machine (UTM) was used for both the tests. Finally, after performing experiments following result was obtained optimum combination of input parameters for Tension Strength is 0.2mm Layer Thickness, 75% Infill Density and 10mm/s Feed Rate which had highest value of S/N ratio 31.0290, while for the flexural optimum combination of parameters are 0.3mm Layer Thickness,50% Infill Density, 10mm/s Feed Rate whose value of S/N ratio is 38.8501*.

***Keywords*: **Polylactic acid (PLA), Effect of process parameters, Fused Deposition modelling (FDM) , Tensile strength , Flexural Strength**

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I. Introduction (*Heading 1*)

In World, there is verities of manufacturing techniques which are used very commonly but as in current scenario of short time requirements one the advanced manufacturing technique is trending which is in general known as Additive Manufacturing. One of the most widely used additive manufacturing technique is Fused Deposition Modelling commonly known as 3-D printing, these techniques is basically based on layer-by-layer manufacturing. Here in these method parts can be built layer by layer through the extruded material filament [1]. These techniques provide the designer the freedom of complex and irregular design as these designs could be easily manufactured by the 3-D printing which is nearly impossible through conventional manufacturing. Also, through these technique products can be built at lower cost and product development cycle is also reduced which is the attractive advantage of the technology [2].

Fused Deposition Modelling (FDM), here the Raw material is in filament form which is heated to temperature where its state changes from solid to the semi-solid form and then it is extruded through the nozzle. Through the nozzle new layer is formed on the previous deposited layer to form the structure. These newly deposited layer gets solidified and comply the previously deposited layer through bonding between layers. So, at last these gives flexibility to build complex geometry [3]. FDM-built part can also be considered as laminated parts composite structure which have vertically stacked layers of raw material, these adds to the mechanical properties of the parts. Though, mechanical properties of the part depend on the raw material filament but it also depends on the orientation and raster angle that produces the anisotropic nature of properties.

Fused Deposition Modelling (FDM) parts are being used in my industries which includes Aerospace industries. Automobile Industries, Medical industries, Electrical industries and many more. FDM parts have many promising application in various industries due to flexibility in manufacturing. So it is necessary to understand the various mechanical properties in detail of the FDM fabricated parts [3].

There are plenty of polymer material available for additive manufacturing technologies. Polylactic acid (PLA) is the most widely used polymer material in additive manufacturing technologies. PLA is the biodegradable polymer that possess good strength and biodegradable property which essential for manufacturing components from 3-D printing [4].

Tensile and flexural strength are the key mechanical properties which is required in any components which is going to be used in any working environment, for example in automobile industries brackets of parking brakes are 3-D printed, these components is being held in tension for most of its working time. Talking about the PLA material, Ultimate tensile strength of the PLA material is Twice the ABS even though the ABS is more brittle [5]. Though tensile and flexural strength various according to various printing parameters such as layer thickness, infill density, feed rate and many such. Layer thickness have major impact on the tensile strength, higher the layer thickness lowers the tensile strength, while for flexural strength it is opposing higher the thickness higher the strength [6]. Similarly, for the feed rate higher feed decreases the tensile and flexural strength [7]. Further we will be seeing effect of printing parameters on the tensile strength and flexural strength in detail.

II. EXPERIMENTAL DETAILS

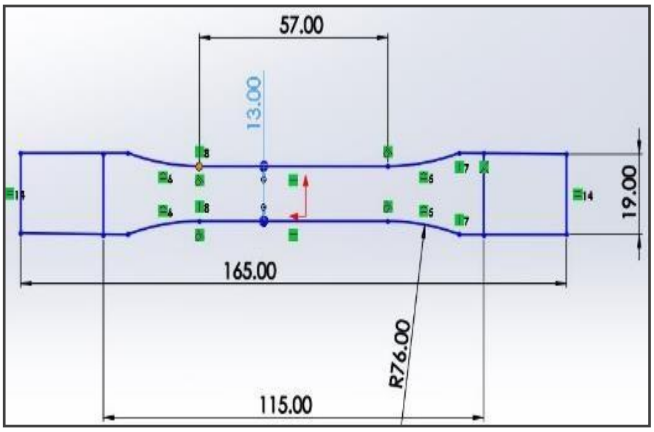
All the tensile and flexural specimens were built by using Wanhao Duplicator and model is I3 plus which is open-source FDM 3D printer. The machine has box size of 500 mm X 500 mm X 300 mm. The machine has a printing volume of 200 mm in X axis, 200 mm in Y axis, and 180 mm in Z axis and layer height of 0.1 to 0.5mm. The printer has a nozzle diameter of 0.4 mm. the bed is heated and having a range of 30 to 100 Degree Celsius. The printer is capable of printing with ABS, PLA, Flexible, Wood, Nylon etc. material with filament diameter of 1.75 mm.

Tensile and flexural strength of the part is significantly affected by the selection of process parameters. Hence, in the present study, three process parameters viz., layer thickness, infill density and feed rate have been selected for investigation on tensile and flexural strength at each of the three levels. The process parameters of FDM can be defined as follows:

(a) Layer thickness – it is thickness of the layer deposited by the nozzle.

(b) Infill density – it is the amount of filament printed inside the object.

(c) Feed rate – it is the speed on which the nozzle feed the material to bed.



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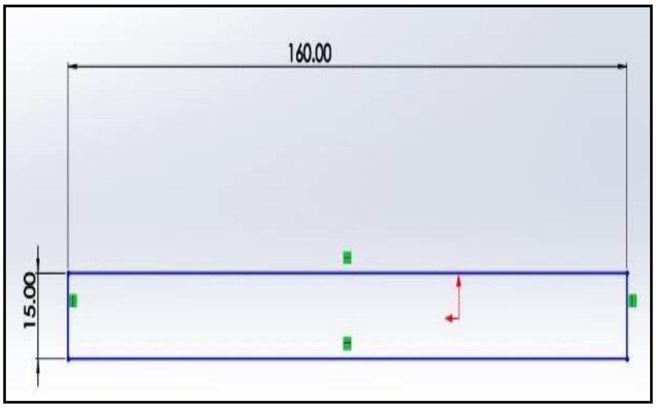


Figure 1: Specimen Model According to ASTM code

Tensile specimen has been designed and fabricated according to ASTM code D638 standard and flexural specimen has been designed and fabricated according to ASTM code D790 shown in Figure 1. Figure 2 represents the schematic diagram of tensile and flexural specimen respectively, where dimension and geometry of test specimen can be seen. SolidWorks software has been used to model the test specimen as per ASTM code and saved as an STL file. The STL file is then imported into Wanhao Cura software (open-source 3D printer software). The Wanhao Cura has been used to control the printer setting, such as layer height, infill density, part orientation, feed rate etc. in which 3 are the process parameters. Finally, the G code file name. Gcode was generated and transferred to the Wanhao Duplicator printer to fabricate the 3D specimen. All the variable process parameters were controlled by Wanhao Cura software

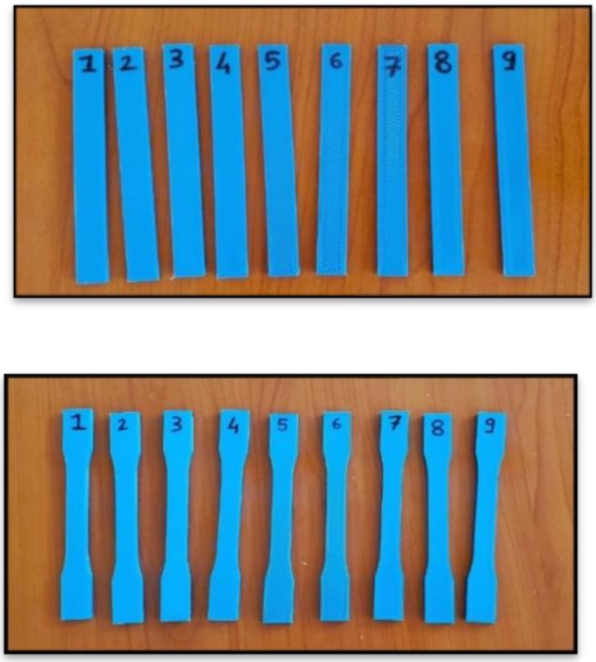


Figure 2 : 3-D printed Tensile and Flexural test specimens.

Tensile and flexural specimen as shown in figure 2 were manufactured using 1.75 mm diameter PLA (polylactic acid) filament. The same spool of the PLA filament has been used to fabricate specimen so that same properties of filament material can be assured.

TINIUS OLSEN/L-Series H50KL machine has been used to perform a tensile and flexural test on the test specimen. The machine equip with 2 load cell one of 5kN and second of 50kN and built-in Horizon software which allows control, monitor and record the measurement data and chars. The machine has extension measure of resolution 0.001 mm. the machine has maximum crosshead travel excluding grips is 1100mm, distance between columns are 405mm, frame stiffness 100kN/mm at normal load points. Test samples were tested until failure at a crosshead speed of 5 mm/min. Test data was recorded through the Horizon software. For tensile and flexural the test setup is different but basic process of testing was same so both testing done in one machine.

Table 1: Taguchi's L9 Orthogonal Array

Input Parameters	Level 1	Level 2	Level 3
Layer Thickness (mm)	0.1	0.2	0.3
Infill Density (%)	25	50	75
Feed Rate (mm/s)	10	40	70

Number of Input Parameters (Factors) = 3

Number of Levels =3

Number of Experiments = 3^3

Now, using Taguchi's L9 Orthogonal Array, the total number of experiments are reduced to 9 from 27 to reduce the cost and improve the productivity.

Table 2: Design of Experiment for Tensile Strength

Sr. No.	Layer Thickness (mm)	Infill Density (%)	Feed Rate (mm/s)
1	0.1	25	10
2	0.1	50	40
3	0.1	75	70
4	0.2	25	40
5	0.2	50	70
6	0.2	75	10
7	0.3	25	70
8	0.3	50	10
9	0.3	75	40

Moreover, in present investigation, the Taguchi's design has been used to perform an experimental run at every combination of the factor levels. Three factors have been varied at the three levels so according to Taguchi L9 experimental design, total 9 number of experiments need to be performed as shown in the Table 2. So here total 18 specimen have to print, 9 for tensile and 9 for flexural. For each experiential run, the process parameters were set according to Taguchi's L9 experimental design

III. RESULT AND DISCUSSION

The tensile and flexural tests were carried out to measure the effects of different values of layer thickness, infill density and feed rate on 3D printed parts.

3.1 Results of tensile strength

Table 3.1.1: Results of Experiment for Tensile Strength

Sr. No.	**Layer Thickness (mm)**	**Infill Density (%)**	**Feed Rate (mm/s)**	**Tensile Strength (N/m^2)**	**S/N Ratio**
1	0.1	25	10	30	29.5424
2	0.1	50	40	27.6	28.8182
3	0.1	75	70	26.2	28.3660
4	0.2	25	40	26.7	28.5302
5	0.2	50	70	29.1	29.2779
6	0.2	75	10	35.6	31.0290
7	0.3	25	70	29.1	29.2779
8	0.3	50	10	35	30.8814
9	0.3	75	40	32.3	30.1841

As discussed above there are 3 different experimental objectives for S/N ratio but here we selected larger the better. That means the highest value of the SN ration shows the significance parameter for tensile testing. The table 3.1.1 shows the results of the experiment. Here the biggest S/N ratio value is 31.0290 which have the highest value of tensile strength 35.6 N/m^2 and the values of layer thickness, infill density and feed rate for the same are 0.2mm, 75% and 10mm/s respectively.

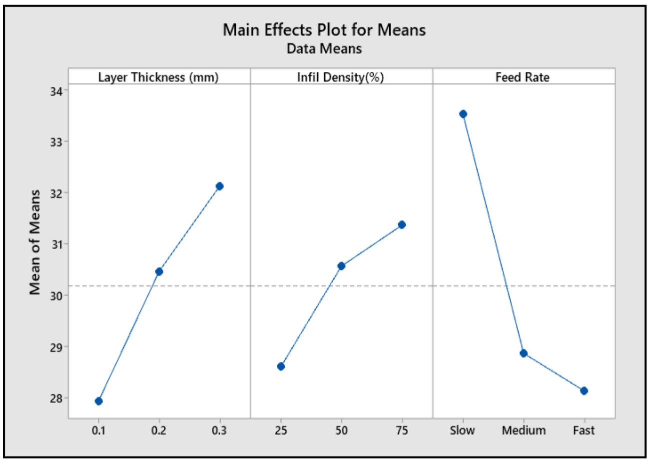
Table 3.1.2: Response table for Signal to Noise

Level	Layer Thickness (mm)	Infill Density (%)	Feed Rate (mm/s)
1	28.91	29.12	30.48
2	29.61	29.66	29.18
3	30.11	29.86	28.97
Delta	1.21	0.74	1.51
Rank	2	3	1

Table 3.1.3: Response table for Means

Level	Layer Thickness (mm)	Infill Density (%)	Feed Rate (mm/s)
1	27.93	28.60	33.53
2	30.47	30.57	28.87
3	32.13	31.37	28.13
Delta	4.20	2.77	5.40
Rank	2	3	1

The table 3.1.2 and 3.1.3 are Response Table for SN Ratio of tensile strength and means of tensile strength respectively, where the rank is selected according to delta values. The rank 1 shows the most significant parameter for tensile strength and it is feed rate for both the tables. Figure 3 shows the main effect plot for SN ratio of tensile strength and means of tensile strength respectively, in which the highest slope is for feed rate in both the figures, which give the significance that the feed rate is most significant parameter for tensile strength



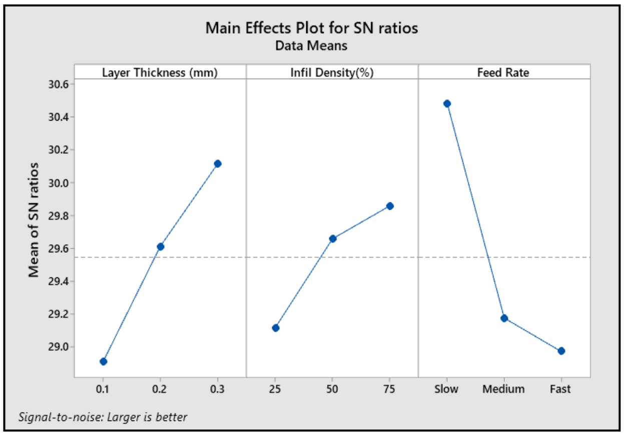


Figure 3: Plots for Means and S/N ratio

The significance of each parameter on tensile strength is also obtained by analyzing the observation through analysis of variance (ANOVA). This analysis gives the main effect of the process parameters on tensile strength. This also direct the effect of independent parameters on tensile strength.

Table 3.1.4: Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer Thickness (mm)	2	26.836	13.418	7.45	0.118
Infill Density (%)	2	12.162	6.081	3.38	0.229
Feed Rate	2	51.476	25.738	14.29	0.065
Error	2	3.602	1.801		
Total	8	94.076			

The table 3.1.4 the ANOVA for tensile strength. The F-value is use to select or reject the parameter. By observing the F-values the highest among all is 14.29 which show the most significant process parameter which is feed rate for tensile strength.

By all the methods the most significant process parameter found is feed rate for tensile strength.

The regression equation for tensile strength is,

Tensile Strength = 30.178 – 2.244 Layer Thickness (mm)_0.1 + 0.289 Layer Thickness (mm)_0.2 + 1.956 Layer Thickness (mm)_0.3 – 1.578 Infill Density (%) _25 + 0.389 Infill Density (%) _50 + 1.189 Infill Density (%) _75 + 3.356 Feed Rate Slow – 1.311 Feed Rate Medium – 2.044 Feed Rate Fast

Regression values are 96.17% for R-sq and 84.68% for R-sq(adj), which is in between 80% to 100% which shows that for tensile testing the regression model is accurate.

3.2 Results of flexural strength

Table 3.2.1: Result of experiment for Flexural Strength

Sr. No.	Layer Thickness (mm)	Infill Density (%)	Feed Rate (mm/s)	Flexural Strength (N/m^2)	S/N Ratio
1	0.1	25	10	74.8	37.4780
2	0.1	50	40	81.7	38.2444
3	0.1	75	70	75	37.5012
4	0.2	25	40	78.7	37.9195
5	0.2	50	70	79.7	38.0292
6	0.2	75	10	80.7	38.1375
7	0.3	25	70	83.7	38.4545
8	0.3	50	10	87.6	38.8501
9	0.3	75	40	85.6	38.6495

Here also we selected bigger is better SN ratio for flexural testing. That means the highest value of the SN ration shows the significance parameter for flexural testing. The table 3.2.1 shows the results of the experiment. Here the biggest SN ratio value is 38.8501 which have the highest value of flexural strength 87.6 N/m^2 and the values of layer thickness, infill density and feed rate for the same are 0.3mm, 50% and 10mm/s respectively.

Table 3.2.2: Response table for Signal to Noise Ratio

Level	Layer Thickness (mm)	Infill Density (%)	Feed Rate
1	37.74	37.95	38.16
2	38.03	38.37	38.27
3	38.65	38.10	37.99
Delta	0.91	0.42	0.28
Rank	1	2	3

Table 3.2.3: Response table for Means

Level	Layer Thickness (mm)	Infill Density (%)	Feed Rate
1	77.17	79.07	81.03
2	79.70	83.00	82.00
3	85.63	80.43	79.47
Delta	8.47	3.93	2.53
Rank	1	2	3

The table 3.3.2 and 3.2.3 are Response Table for SN Ratio of flexural strength and means of flexural strength respectively, where the rank is selected according to delta values. As we know the rank 1 shows the most significant parameter for flexural strength and it is layer thickness for both the tables. Figure 4 show the main effect plot for SN ratio of tensile strength and means of tensile strength respectively, in which the highest slope is for layer thickness in both the figures, which give the significance that the layer thickness is most significant parameter for tensile strength.

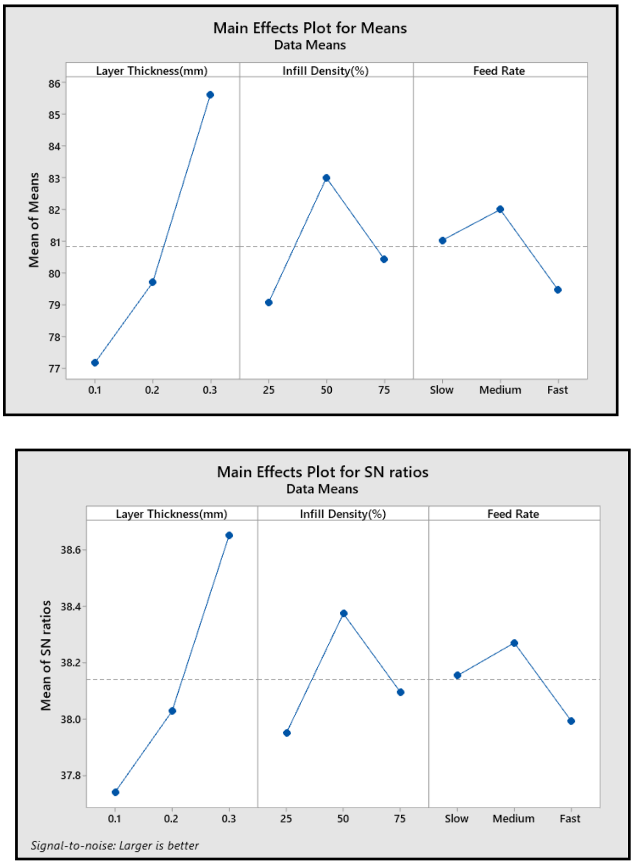


Figure 4 : Plots for Means and S/N ratio

Table 3.3.4: Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer Thickness (mm)	2	113.307	56.653	16.86	0.056
Infill Density (%)	2	23.927	11.963	3.56	0.219
Feed Rate	2	9.807	4.903	1.46	0.407
Error	2	6.720	3.360		
Total	8				

The table 3.2.4 the ANOVA for flexural strength. The F-value is use to select or reject the parameter. By observing the F-values the highest among all is 16.86 which show the most significant process parameter which is layer thickness for flexural strength.

By all the methods the most significant process parameter found is layer thickness for flexural strength.

The regression equation for tensile strength is,

Flexural Strength = 80.833 – 3.667 Layer Thickness (mm)_0.1 – 1.133 Layer Thickness (mm)_0.2 + 4.800 Layer Thickness (mm)_0.3 – 1.767 Infill Density (%) _25 + 2.167 Infill Density (%) _50 –

0.400 Infill Density (%) _75 + 0.200 Feed Rate Slow + 1.167 Feed Rate Medium – 1.367 Feed Rate Fast

Regression values are 95.63% for R-sq and 82.52% for R-sq(adj), which is in between 80% to 100% which shows that for flexural testing the regression model is accurate.

IV. CONCLUSION

Through various experiment performed separately for both tensile strength and flexural strength, it was found various input parameter have their impact on the both the mechanical property. Further on learning the results in detail it was observed that not the same input parameter have Eventually after performing nine experiment each for both tensile and flexural strength we concluded that optimal combination for tensile strength is 0.2(mm) layer thickness , highest infill density of 75 % and lowest feed rate of 10 mm/s which give Signal-to-noise ratio of 31.0290 , while for flexural strength values are 0.3 mm of layer thickness, average infill density of 50% and again the lowest feed rate of 10 mm/s which signal-to-noise ratio of 38.8501.

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