ISSN: 2350-0328
International Journal of AdvancedResearch in Science, Engineering and Technology
Vol. 12, Issue 5, May 2025

Optimization of Process Parameter of Fused Deposition Modelling Printer for PLA PRO material

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ABSTRACT: Polylactic Acid (PLA) is a chloric, thermoplastic; as a biodegradable material from renewable materials, this is a good fit for sustainable 3D printing applications. This work aimed to determine Fused Deposition Modelling (FDM) printer parameters for using Taguchi analysis to increase tensile strength and decrease weight of PLA printed parts. The input parameters that were selected for testing were: Layer thickness Print speed Infill density Infill pattern The approach taken was Design of Experiments (DOE) and involved using a Taguchi L9 orthogonal array to systematically obtain experiments. Through analyses, the optimal set of parameters was established, and confirmation tests showed that the output parameters improved after applying the optimal parameters. ANOVA also established that infill density was the most significant contributor to both tensile strength and weight of the printed parts. The work recommends the optimal parameters that was identified to improve the output performance of FDM 3D printers, and the sustainable use of PLA material.

KEYWORDS: FDM Printing, Design of Experiment, ANOVA, Taguchi, PLA PRO

I. INTRODUCTION OF FDM PROCESS

Fused Deposition Modeling, or FDM, is one of the most popular types of additive manufacturing, appreciated for its ease of use, low cost, and ability to create intricate three-dimensional shapes from computer models. In this method, the thermoplastic filament is heated and softens to the point where it can be extruded through the nozzle of a machine. [1]The thermoplastic material is deposited in layers that are controlled to match a predefined design. Consequently, FDM permits fast designing and manufacturing of parts that are functional out of many materials such as PLA, ABS, or PETG composites, thus serving the needs of engineering, healthcare, automotive, and consumer goods industries. Nonetheless, FDM-printed parts are subject to several process parameters: layer thickness, infill density, printing speed, and build orientation, which affect the mechanical strength and geometric precision of printed parts, requiring optimization for different applications.[2]

II. LITERATURE REVIEW

FDM gives smooth surface finish on complex geometries which enhances the performance and aesthetics of printed parts.[3] The advanced printing methods highlights the possible impact of FDM technology in addressing the repurposing of waste materials into high quality filaments for healthcare, sustainable design, and other innovative fields, thus promoting eco-friendly manufacturing practices.[4]

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With the advancement of FDM printers, their capability to incorporate multi-material printing that can carve out complex structures with customized features improves as well. An example of this is dual-nozzle systems which allow the use of different materials at the same time which enables the designing of objects that incorporate multifunctional mechanical properties, for example, flexible joints and rigid supports.[5] "Custom medicine" where specialized implants can be designed to improve functionality for specific patients can be addressed with new research. Such advancements will capture the flexibility of new 3D printing technologies. Furthermore, FDM technology has profound applications outside of healthcare including aerospace and electronics, as the ability to fabricate fully inorganic components could revolution the industry. While looking into the possibilities of FDM technology, researchers are also looking at its uses for sophisticated systems of drug delivery taking advantage of the 3D printed materials. With better control and addition in improved treatment of multi-material and biocompatible polymers researchers can fabricate a device for release of drugs.[6]With the geometrical and material capabilities of the FDM process, complex components can be manufactured.[7] Transformative healthcare solutions can be possible with the potential applications which are far beyond traditional manufacturing.

Besides the development in drug delivery systems, FDM technology is gaining great momentum in the field of tissue engineering as well, where the development of scaffolds with properties similar to natural extracellular matrices is pivotal for the proper growth of cells and regeneration of tissues. Through the use of biocompatible thermoplastic polymers, scientists can produce complex structures that not only ensure cellular attachment but also provide room for nutrient perfusion through engineered microchannels, thus increasing the overall viability of the tissue.[3] This ability enables the fabrication of patient-specific implants customized to match anatomical differences, minimizing rejection rates and enhancing healing success. Additionally, as demand for personalized medicine continues to expand, the inclusion of artificial intelligence within the design process can make customization of such constructs more efficient, facilitating fast prototyping and test iteration that can greatly hasten clinical implementation. Therefore, the continuous development of FDM printers is set to reshape not just manufacturing procedures but also the future of regenerative medicine.

As FDM technology advances, its applications reach into the field of sustainable manufacturing processes, specifically in the utilization of recycled materials. Through recycling waste thermoplastics into high-quality filaments for 3D printing, companies can greatly minimize their environmental impact while ensuring performance levels in biomedical applications. Not only does this method tackle the increasing issue of plastic waste, but it also supports global sustainability efforts by facilitating a circular economy in the additive manufacturing industry. For optimization of process parameters of FDM GRA method is used. GRA is multi-response optimization technique. The researcher method was used for optimization of AWJM process parameters and the findings highlight that careful tuning of parameters such as traverse speed, abrasive flow rate, and standoff distance can significantly enhance machining performance, making it more efficient and effective for this challenging material. [8]

III.EXPERIMETAL SETUP

For the experimentation Flashforge Guider IIs printer is used. The Flashforge Guider IIs is a professional-grade Fused Filament Fabrication (FFF) 3D printer designed for high-quality, large-volume printing. It offers a substantial build volume of 250 × 280 × 300 mm and supports a variety of filaments, including PLA, ABS, PETG, TPU, and wood-filled materials, thanks to its 0.4 mm nozzle and heated glass bed. The ASTM D638 standard parts are printed using different combinations of the parameters.

FlashPrint 5.0 software was utilized for slicing the 3D model of the ASTM D638 standard tensile specimen. This software, developed by FlashForge, offers an intuitive interface and robust slicing capabilities tailored for FDM 3D printing. Key slicing parameters such as layer height, infill density, print speed, and number of shells were configured to ensure dimensional accuracy and structural integrity of the printed specimen. The sliced file generated by FlashPrint 5.0 was then exported in G-code format for subsequent 3D printing. The software's compatibility with FlashForge printers ensured seamless integration between the slicing process and actual printing. Additionally, the preview feature in FlashPrint 5.0 allowed verification of layer-by-layer toolpaths, aiding in minimizing print defects and optimizing material usage.

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International Journal of AdvancedResearch in Science, Engineering and Technology
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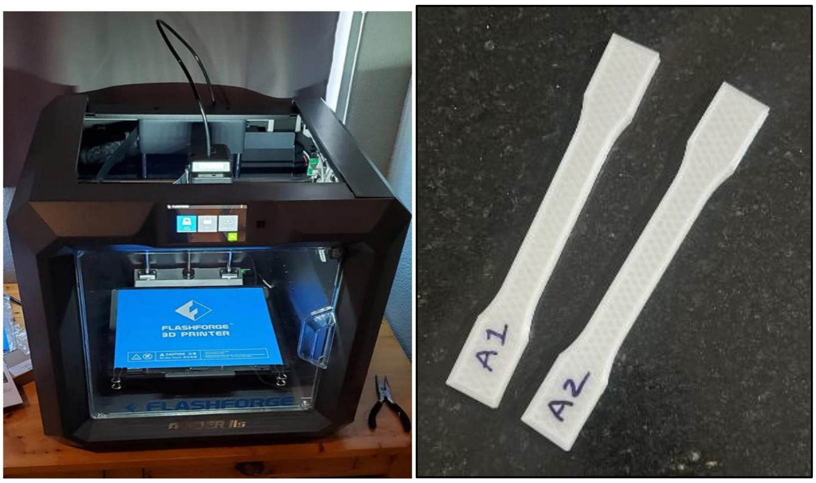

Fig 1: Flashforge Guider IIs printer and ASTM D638 Standard component

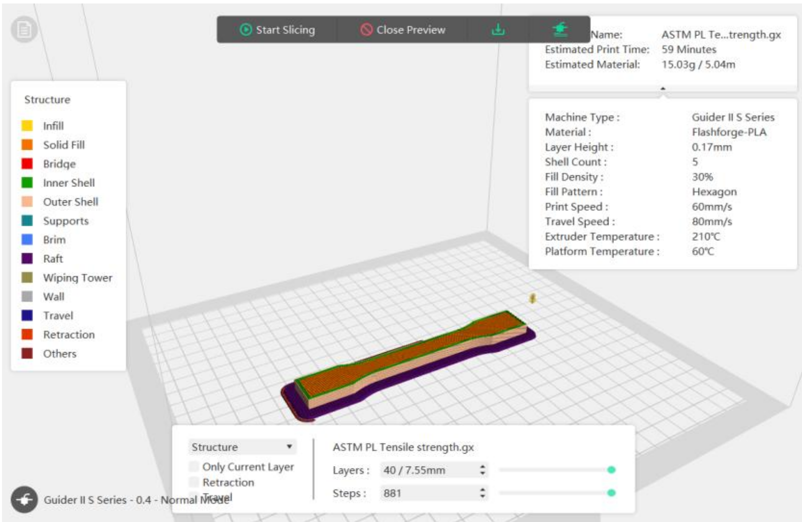

Fig 2: Slicing of component using Flashprint 5.0 software

IV.MATERIALS & METHOD

Polylactic Acid (PLA), a biodegradable thermoplastic obtained from renewable sources, was chosen as the material for this research because of its extensive application in Fused Deposition Modeling (FDM) and good mechanical properties for prototyping purposes. 1.75 mm diameter commercially available PLA PRO filament was utilized to produce the test specimens.

To maximize the tensile strength and weight separately, the Taguchi approach was utilized as a design of experiments tool. An L9 orthogonal array was chosen based on the number of process parameters and their levels. The important FDM parameters like layer thickness, print speed, infill density, and infill pattern were systematically varied across experiments. Each parameter was tested at three levels. Specimens were prepared by following ASTM D638 standards for tensile testing. Weight of printed parts was measured using a precision digital balance. The table shows the property of PLA PRO material used for testing.

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Table 1: Mechanical Properties of PLA PRO material

Material	Property	Value	Unit
PLA PRO	Tensile Strength	50–65	MPa
	Tensile Modulus	3000–3800	MPa
	Elongation at Break	6–10	%
	Flexural Strength	80–100	MPa
	Flexural Modulus	3000–3500	MPa
	Impact Strength (Izod)	20–45	J/m

Following is the table for process parameters and their level used for the design of experiment.

Table 2: Parameters and its Levels for FDM Printer

Parameter/Level	1	2	3
Printing speed	60	90	120
Layer Thickness	0.17	0.25	0.33
Infill Density	30	60	90
Infil pattern	Hex	Triangle	3d infill

As there are 4 parameters and 3 levels considered for optimization, using MINITAB software Taguchi L9 array is used for the experimentation. The combination of the experimentation with the response values are as shown in the table below.

Table 3: L9 array with the response values

Printing speed (mm/s)	Layer Thickness (mm)	Infill Density (%)	Infill pattern	Tensile Strength (MPa)	Weight (gm)
60	0.17	30	hex	16.64	10.2
60	0.25	60	triangle	22.15	12.18
60	0.33	90	3dinfill	26.05	13.88
90	0.17	60	3dinfill	17.9	13.23
90	0.25	90	hex	21.55	15.12
90	0.33	30	triangle	21.95	11.31
120	0.17	90	triangle	23.95	16.16
120	0.25	30	3dinfill	16.55	9.8
120	0.33	60	hex	21.8	13.34

Tensile strength was assessed by a universal testing machine (UTM). The tests were conducted under laboratory conditions, and the highest tensile strength values were noted for every specimen. Three readings were taken for every trial, and the average of the three was used to avoid results being influenced by any reading.

For concurrent optimization of tensile strength (to be maximized) and weight (to be minimized), Grey Relational Analysis was utilized. The experimental data were initially normalized, and the Grey Relational Coefficients (GRC) were determined. Then, the Grey Relational Grade (GRG) was determined for every experiment, which acted as a performance index to determine the optimal parameter settings.

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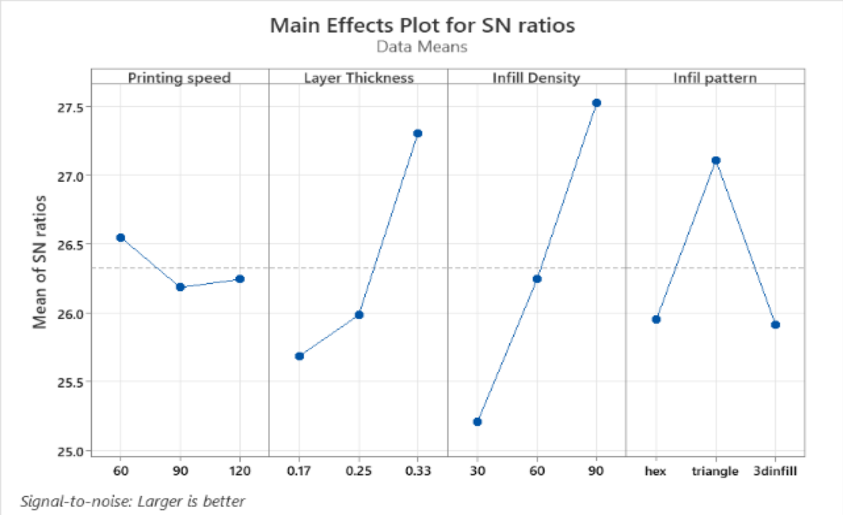
V.RESULT & DISCUSSION

Taguchi analysis is carried out for Tensile strength with larger the better consideration.

Table 4: Response Table for Signal to Noise Ratios

Level	Printing speed	Layer Thickness	Infill Density	Infil pattern
1	26.55	25.69	25.21	25.95
2	26.18	25.98	26.24	27.11
3	26.24	27.30	27.52	25.92
Delta	0.36	1.62	2.31	1.19
Rank	4	2	1	3



Graph 1. Mean effect plot for SN ratios of tensile strength

Table 5: Analysis of Variance for Tensile strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	67.276	22.425	6.06	0.040
Printing speed	1	1.075	1.075	0.29	0.613
Layer Thickness	1	21.319	21.319	5.76	0.062
Infill Density	1	44.881	44.881	12.13	0.018
Error	5	18.495	3.699		
Total	8	85.771			

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The ANOVA results indicate that infill density significantly affects tensile strength ($P = 0.018$), while layer thickness shows a marginal effect ($P = 0.062$) and printing speed has no significant impact ($P = 0.613$). With a regression P-value of 0.040, the overall model is statistically significant, confirming that the selected parameters collectively influence tensile strength, with infill density being the most dominant factor.
From the analysis it is concluded that infill density is most influential parameters for tensile strength. For maximum tensile strength printing speed at level 1, layer thickness and infill density at level 3 and infill pattern at level 2 combination must be used. The combination is given as 60-0.33-90-triangle. The conformation test is carried out and the tensile strength is found out as 27.22 MPa.

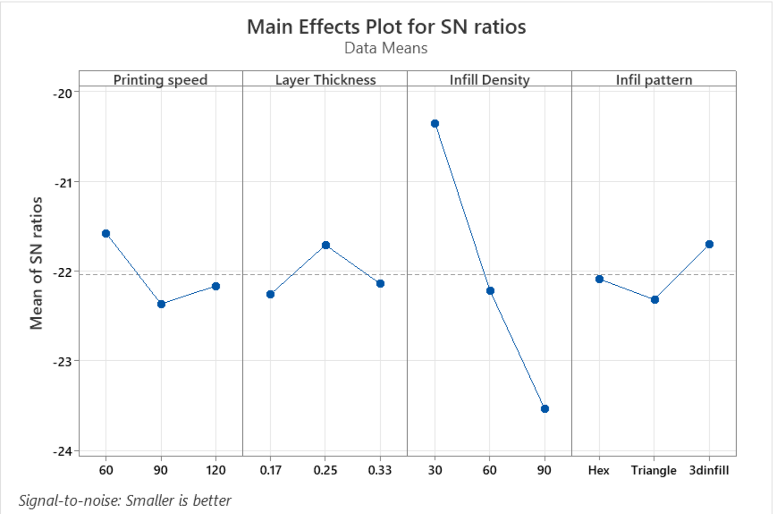
Table 6: Tensile strength value after confirmation test

For Tensile Strength	
Optimum Parameter	Experimental Value
60-0.33-90-triangle	27.22 MPa

Taguchi analysis is carried out for weight of the component with lower the better consideration.

Table 7: Response Table for Signal to Noise Ratios

Level	Printing speed	Layer Thickness	Infill Density	Infil pattern
1	-21.58	-22.26	-20.36	-22.09
2	-22.36	-21.71	-22.22	-22.32
3	-22.17	-22.14	-23.54	-21.70
Delta	0.79	0.55	3.18	0.62
Rank	2	4	1	3



Graph 2. Mean effect plot for SN ratios of weight

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Table 8: Analysis of Variance for Weight

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	3	33.6979	11.2326	18.84	0.004
Printing speed	1	1.5403	1.5403	2.58	0.169
Layer Thickness	1	0.1873	0.1873	0.31	0.599
Infill Density	1	31.9704	31.9704	53.62	0.001
Error	5	2.9814	0.5963		
Total	8	36.6794			

The ANOVA results for component weight show that infill density has a highly significant effect (P = 0.001) and is the dominant factor influencing weight. Printing speed and layer thickness have no significant impact, with P-values of 0.169 and 0.599, respectively. The overall regression model is statistically significant (P = 0.004), indicating that the selected parameters do influence the component's weight, with infill density being the primary contributor.
From the analysis it is concluded that infill density is most influential parameters for weight. For maximum tensile strength printing speed at level 3, layer thickness 3, infill density at level 2 and infill pattern at level 1 combination must be used. The combination is given as 120-0.33-60-hex. The conformation test is carried out and the weight is found out as 9.1 gm.

Table 9: Weight of the component value after confirmation test

For weight	
Optimum Parameter	Experimental Value
120-0.33-60-hex	9.1 gm

VI. CONCLUSION

From the experimental assessment, we observe that infill density is a predominant factor influencing both the tensile strength and the weight of the component in PLA PRO 3D printing. The best parameter for triangled pattern with maximum infill of 90% and minimum weight of 9.1g was found to be 60 mm/s, 0.33 mm, while the hex pattern with 60% infill achieved the minimum weight at 120 mm/s, with validation tests confirming 27.22 MPa tensile strength and 9.1 g weight. The results illustrate the potent application of process optimization in this case study using Taguchi and ANOVA methods. Subsequent work can investigate alternative infill patterns, material combinations, or optimize for competing objectives, such as mechanical strength and lightweight design tailored to specific applications.

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