Experimental research on the effects of machine process parameters on the compressive and flexural strength of PLA material printed using FDM

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ABSTRACT

KEYWORDS

Polylactic Acid (PLA),
3D Printing,
Fused Deposition Modeling (FDM),
Additive Manufacturing (AM).

Polylactic acid (PLA), also known as polylactide, is a thermoplastic polyester that is commonly used in Fused deposition modeling (FDM) 3D printing and is considered one of the world's far more widely used bio-plastics. PLA is considered biodegradable and environmentally beneficial, unlike petrochemical-based polymers. This is a low-cost product that could be used in a variety of applications, including food packaging, tissue scaffolding, and biomedical devices. This proposed study is primarily concerned with an in-depth investigation of polylactic acid's mechanical strength and its optimization. The L-9 orthogonal array is adopted by utilizing the Taguchi design of experiments, with input characteristics such as Printing speed, Infill density, and Layer height for the fabrication of nine different sets of flexural and compressive specimens as per ASTM standards using FDM. The responses such as compressive strength and flexural strength are optimized using Taguchi Analysis – S/N Ratios and ANOVA. Similarly, this research reveals a statistical link between input elements and responses. According to the current study, the ideal parameter levels for Flexural and Compression strengths have been found and confirmation Tests have also been conducted according to the optimized process parameter levels as obtained in the Taguchi analysis.

1. Introduction

The higher quality of things available to us now is largely responsible for the benefits of civilization that we now enjoy. The increase in product quality can be achieved by a proper design that takes into account both functional and production needs. Manufacturing, in its broadest meaning, is the process of turning raw materials into finished items, and it includes the design and manufacture of commodities utilizing a variety of methods and techniques. The manufacturing sector is classified into two types which are Subtractive manufacturing and Additive manufacturing. Subtractive manufacturing is a process of manufacturing in which casting is the first process and then the material is subtracted from the casted product to get the required design or required product.

Additive manufacturing (AM) is a fabrication technique that employs computer-aided design (CAD) data to create key geometry, functioning prototypes, and machine parts. When compared to traditional machining, the notion of manufacturing an item is to add material layer upon layer without subtracting any unnecessary materials from the material block. A range of printing materials, including ABS, PLA, Nylon, PETG, and others, are utilized as input materials in the FDM technique to create 3D objects. Polylactic acid (PLA) is among the most widely utilized polymeric materials in 3D printing. PLA is recyclable aliphatic polyester derived from lactic acid, which is found in sugar, cassava, maize starch, and other foods. PLA has a lot of benefits, such as high strength and hardness, recyclability, and low toxicity. To present, only a few studies on the mechanical properties of 3D-printed PLA polymer have been published. Furthermore, as a result of recent increases in oil prices and key improvements in polymerization methods, PLA's price competitiveness has increased. The properties of filament-stored PLA are shown in Table 1.

2. Literature Review

- PLA material

PLA is a linear aliphatic thermoplastic polyester derived from 100% renewable resources such

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Table 1
Properties of PLA filament.

Property	Unit	Value
Melting Temperature	°C	54-56
Elongation at the break	%	9
Rockwell Hardness	-	85 (SHD)
Flexural Strength	MPa	108
Ultimate Tensile Strength	MPa	50
Tensile Modulus	GPa	1.230
Density	g/cm^3	1.24

as sugar, corn, potatoes, cane, beet, etc. The stereochemistry and molecular weight of PLA have a significant impact on its fascinating physical characteristics, as well as its biocompatibility and biodegradability. In addition, it is easily processed into a desired configuration on standard plastic equipment to yield molded parts, films, or fibers. Owing to these properties, PLA has a wide range of potential industrial applications. Due to its initial production costs, the starting applications of PLA have been focused on high-value products, particularly medical devices. However, its price has been falling as production increases and new methodologies for high molecular weight PLA are developed. PLA's potential for consumer products such as packaging is remarkable due to its transparency, low toxicity, and environmentally benign characteristics (Armentano et al., 2013). PLA and its copolymers have been employed in a variety of wound treatment applications, including surgical sutures, mending dental extraction wounds, and reducing postoperative adhesions. In drug delivery systems (DDS), the medication might be administered continuously for varying amounts of time, up to a year. In this application, a variety of polymers, including biodegradable polymers like PLA, were employed. Numerous medications have been encapsulated using PLA and their copolymers as nanoparticles. The findings suggested that PLA NPs might be good candidates for the development of drug delivery systems that target active chemicals in hair follicles (Hamad et al., 2015). According to Sreekumar et al. (2021) PLA fibers are being extensively researched for a variety of applications. The distinctive qualities of PLA fibers, such as their natural softness, simplicity of processing, and resistance to stains and soil, enable them to be used in a variety of fiber-based products. Hollow fiberfill for pillows and comforters, bulk continuous filament for carpets, filament yarns and spun yarns for clothing, spun bond and other nonwovens, bicomponent fibers for binders, and self-crimping fibers are some of the current uses for fibers. Additionally, non-woven textiles including furniture, awnings, hygiene items, and diapers employ PLA fibers.

• Influential parameters

Even though various research works are being conducted on fused deposition modeling, only a few researches were established for fused deposition modeling of PLA materials. Mohamed et al. (2015) examined the work done so far in establishing and optimizing the FDM method's process parameters. Many statistical designs of experiments and also optimization strategies for determining the best process parameters were investigated. The current state of FDM research in this field is discussed, as well as the potential for future FDM research in this area. In another study, the impact of three input parameters, such as layer height, raster angle, and raster width on the tensile properties of FDF-printed PLA was investigated using ANOVA analysis, and it was observed that parts printed at a 0° raster angle have better tensile strength than parts printed at a 90° instead (Rajpurohit & Dave, 2019). Shanmugasundar et al. (2019) investigated that Tungsten inert gas (TIG) welding was utilized to test on Austenitic Stainless Steel (AISI 304L), and Taguchi L9 DOE and analysis were employed to optimize the process parameters. In another study, Hikmat et al. (2021) used Polylactic acid (PLA) filament to explore the influence of various printing parameters such as raster orientation, build orientation, nozzle diameter, infill density, extruder temperature, extruding speed, and shell number on tensile strength. Taguchi's mixed model fractional factorial design was used to build up eighteen trials, and PLA specimens were printed on an FDM 3D printer and evaluated for tensile strength using universal testing equipment. The optimal combination of parameters was then determined using the S-N Ratio and ANOVA was performed to identify the key parameters and their impact on tensile strength. In addition, a simple regression model was created to evaluate the tensile strength of the printed part with just three of the process parameters, nozzle diameter (0.5), build orientation (on-edge), and infill density (100%), which were statistically influential and had a strong effect on the outcome, with build orientation getting the largest influence on tensile strength (44.68%).

- Mechanical characterization

Various theoretical concepts and numerical analysis approaches were used to improve the mechanical properties. Lee et al. (2005) investigated process parameters using an orthogonal array, the SN Ratio, primary effect, and ANOVA to produce optimal elastic effectiveness of an aligned ABS design to obtain high throwing distance from the prototype. The elastic quality of the compliant ABS design was found to be considerably affected by FDM settings, raster angle, layer thickness, and air gap. Lee et al. (2007) used cylindrical parts made with FDM, 3D printers, and Nanocomposite deposition (NCDS) to study the effect of construction orientation on compressive strength. Because axial FDM specimen has an 11.6 percent higher compressive strength than transverse FDM specimen, diagonal specimens have the highest compressive strength. The structure of PLA/ABS blends was successfully regulated by a 10% PEG content, according to Jianming Zhang et al. (2016) and the mechanical properties also improved with the increased molecular weight of PEG. In a study conducted by Liu et al. (2017) the grey Taguchi approach was used to improve the mechanical characteristics of a 3D-printed PLA specimen. It's been discovered that layer height and orientation are important for tensile strength, flexural strength, and impact strength. In another study, the mechanical properties of carbon fiber-reinforced PETG thermoplastics were investigated using ASTM standards to fabricate nine batches of both tensile and flexural samples. The samples were 3D printed using the following criteria: layer height, print speed, and infill density. To improve the results of tensile, flexural, and hardness tests, the Taguchi L9 trial approach is applied. Numerous factors have important effects on strength, and ANOVA analysis is used to statistically propose a relationship between factors and responses. The optimum tensile, flexural, and hardness values were found to be 31.567 MPa, 35.045 MPa, and 67.0011 BHN, respectively, in this investigation. The most ideal machine specifications were discovered to be a print speed of 60 mm/sec, a layer height of 200 mm, and an infill density of 80% (Kumar et al., 2020). Dev and Srivastava (2019) investigated the additive manufacturing potentials of bio-inspired infill designs. All of the infill patterns were influenced by nature. Material consumption and mechanical strength of compressive strength have been analyzed in connection to a variety of factors, including Build orientation, Layer thickness, and Infill patterns with various densities. When Fused Deposition Modelling (FDM), 3D printing materials fail under a tensile strain, Yao et al. (2020) revealed two separate failure modes and a particular separation angle that is the demarcation point between the two different failure modes. The qualities of various 3D-Printing materials vary depending on the input parameters and also the type of printing methods employed, according to the literature. As a result, an attempt was made in this study to print PLA material using the 3D-printing technique i.e. FDM, and to optimize input machine parameters for mechanical attributes namely flexural strength and compression strength.

3. Experiment Details

To Produce the samples, the Fused Deposition Modelling (FDM) technique was utilized following the Design of Experiments and Levels listed in Table 2. The samples were produced according to ASTM standards (ASTM D 695 for Compression Strength and ASTM D 790 for Flexural Strength) as shown in Fig. 1, with various characteristics including layer height, infill density, and printing speed taken into consideration. Various mechanical tests, including compression and flexural, are used to determine the output of these samples and the impact of process factors. The machine parameters are optimized using the L9 Taguchi method, and the tested results are examined statistically to identify the connection between them. Fig. 2 depicts the 3D printing machine used for printing samples. The flexural

Table 2
Levels and factors of the process.

S.NO	**Factor**	**Levels**		
		1	**2**	**3**
1	Layer Height (microns)	100	200	300
2	Infill Density (%)	50	70	80
3	Printing Speed (mm/sec)	40	60	80

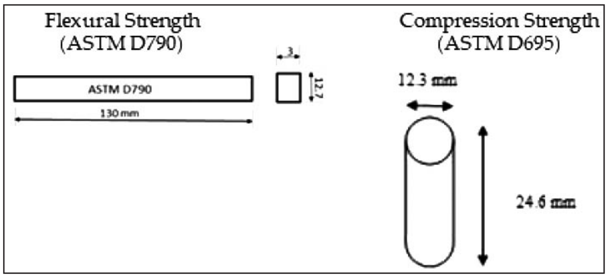

Fig. 1. Sample drawing for testing as per ASTM standards.

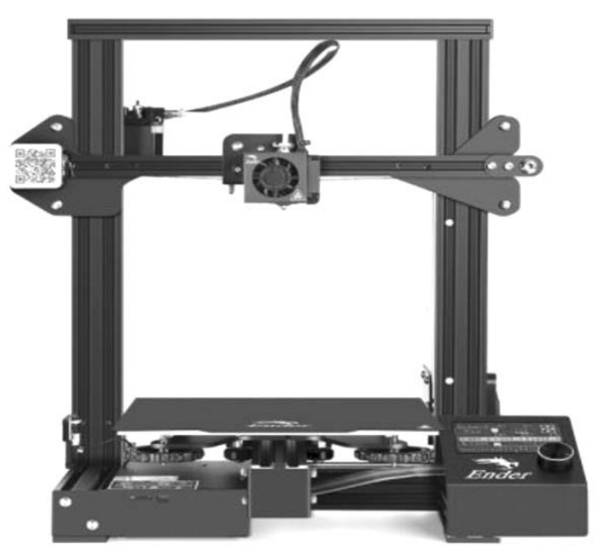

Fig. 2. 3D printing machine.

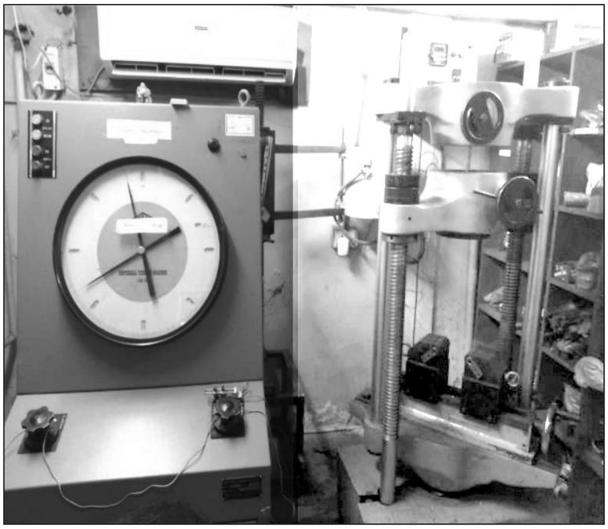

Fig. 3. 40-TON universal testing machine.

and compression strength analysis was conducted on a Universal Testing Machine as shown in Fig. 3, available at Omega Inspection and Analytical Laboratory, Chennai, Tamil Nadu, its specifications are shown in Table 3 and the results were tabulated in Table 4. The flexural and compression strength samples are represented in Fig. 4.

4. Results and Discussion

The input process parameters and their operating ranges are chosen based on research and trial and error. Run 8 has a greater flexural strength of 67.59 MPa, while run 3 has a higher compression

Table 3
Specifications of UTM machine.

Model	:	UTE 40
Max Capacity	:	400 KN
Measuring Range	:	0 – 400 KN
Clearances between columns	:	500 mm
Power supply	:	3Ø, 440 V, 1.7 KW

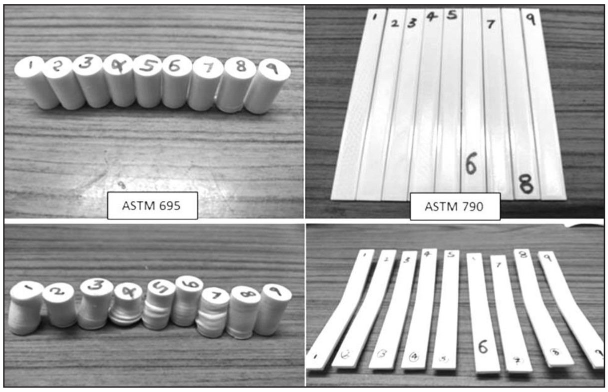

Fig. 4. PLA Samples pre and post-testing.

Table 4
Testing results of flexural and compression strength.

Specimen	Layer height (microns)	Infill density (%)	Printing speed (mm/sec)	Flexural strength (MPa)	Compression Strength (MPa)
1	100	50	40	43.73	35.01
2	100	70	60	45.12	44.73
3	100	80	80	45.81	50.72
4	200	50	60	47.01	31.21
5	200	70	80	46.14	38.93
6	200	80	40	67.52	41.46
7	300	50	80	63.51	28.34
8	300	70	40	67.59	34.15
9	300	80	60	66.09	40.00

strength of 50.72 MPa, according to the experimental data.

From the SN ratio response for flexural in Table 5 and compression results in Table 6 and experimental results, it is observed that Layer height, Level 3 (300 microns), is the most significant parameter for Flexural strength and Infill density, Level 3 (80%), is the most important parameter for compression strength. From the main effects plots for SN Ratios, as shown in Fig. 5, it is found that layer height at Level 3, infill density at Level 3, and printing speed at Level 1 which is A3B3C1 (i.e. Layer height - 300 microns, Infill density - 80%, Printing speed - 40mm/sec) and layer height at Level 1, infill density at Level 3 and printing speed at Level 3 which is A1B3C3 (i.e. Layer height 100 - microns, Infill density - 80%, Printing speed - 80mm/sec) are the optimal parametric conditions predicted to get higher values for flexural strength and compression strength respectively.

From Table 7, it is found that the parameter layer height is the most contributing factor followed by infill density and printing speed for flexural strength. The P-value 0.102 for layer height is the most significant at a 95% confidence interval.

Table 8 shows that for compression strength, the parameter infill density is the most important element, followed by layer height and printing

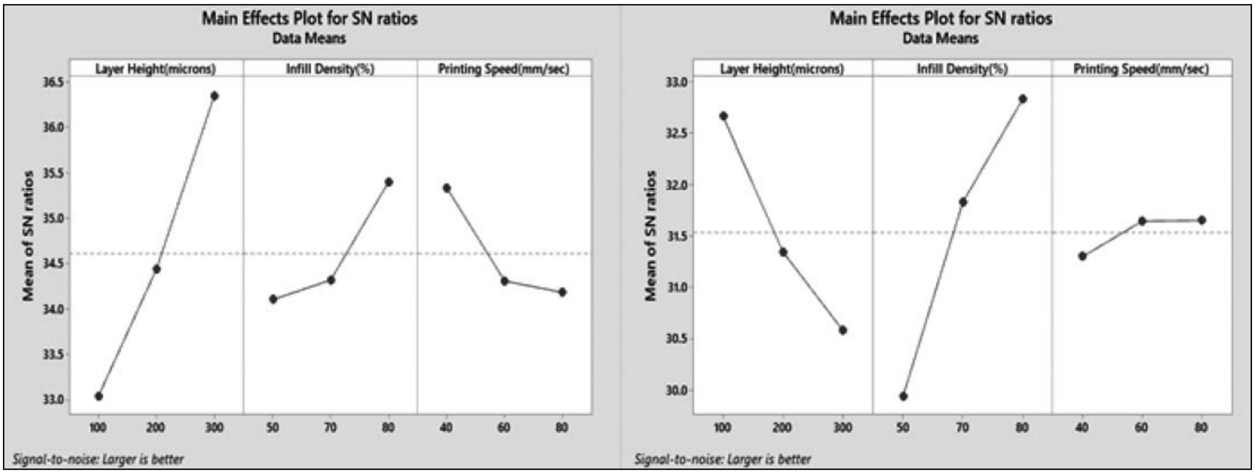

Fig. 5. Main effect plots for SN ratios of flexural and compression strength respectively.

Table 5

SN ratio response table for flexural strength.

Levels	Layer Height (A)	Infill Density (B)	Printing Speed (C)
1	33.04	34.11	35.33
2	34.44	34.32	34.31
3	36.35	35.40	34.19
Delta	3.31	1.30	1.15
Rank	1	2	3

Table 6

SN ratio response table for compression strength.

Levels	Layer Height (microns)	Infill Density (%)	Printing Speed (mm/sec)
1	32.67	29.94	31.30
2	31.35	31.83	31.65
3	30.59	32.83	31.65
Delta	2.08	2.89	0.35
Rank	2	1	3

Table 7

ANOVA for response model flexural strength.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer Height (microns)	2	657.80	68.42%	657.80	328.90	8.77	0.102
Infill Density (%)	2	119.76	12.46%	119.76	59.88	1.60	0.385
Printing speed(mm/sec)	2	108.83	11.32%	108.33	54.41	1.45	0.408
Error	2	75.02	7.80%	75.02	37.51		
Total	8	961.41	100.00%				

Table 8
ANOVA for response model compression strength.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Layer Height (microns)	2	135.668	35.11%	136.668	67.834	166.57	0.006
Infill Density (%)	2	240.258	62.18%	240.258	120.129	294.99	0.003
Printing speed (mm/sec)	2	9.647	2.50%	9.647	4.823	11.84	0.078
Error	2	0.814	0.21%	0.814	0.407		
Total	8	386.388.41	100.00%				

Table 9
Fit for the response model flexural and compression strength.

Models	Flexural Strength	Compression Strength
R-sq	92.20%	99.79%

Table 10
Confirmation test results for flexural predicted levels.

S.no	Response	Predicted Level	Confirmation Test
1	Flexural Strength	A3B3C1	69.65 MPa

speed. At a 95% confidence range, the P-values 0.006, 0.003, and 0.078 of all input factors are the most significant. In Table 9, the R-Square values for the response terms derived as flexural strength (92.20%) and compression strength (99.79%) are observed as being nearer to 100%.

Confirmation Test

The confirmation test has been done for the predicted parameter levels and their results are noted in Table 10.

5. Conclusion

Three input parameters were used to investigate the flexural and compression strength of PLA specimens generated by an FDM 3D printer. To set the experiments, the Taguchi Orthogonal array was used. As a result of the findings, the following conclusions can be drawn:

- By using the Taguchi concept of SN Ratios, it can be concluded that layer height at Level 3, Infill density at Level 3, and printing speed at Level 1 [A3B3C1] (i.e. Layer Height = 300microns, Infill Density = 80%, Printing Speed = 40mm/sec) is the optimum process parametric condition that yielded the highest flexural strength.
- By using the Taguchi concept of SN Ratios, it can be concluded that layer height at Level 1, Infill density at Level 3, and printing speed at Level 3 [A1B3C3] (i.e. Layer height = 100microns, Infill density = 80%, Printing Speed = 80mm/sec) is the optimum process parametric that yielded the highest compression strength values.
- By ANOVA, it is observed that Layer height is the most significant parameter with a contribution of 68.42% for flexural strength and Infill density is the most significant parameter with a contribution of 62.18% for compression strength.
- Finally, the confirmation test was performed for the level [A1B3C3] (i.e. Layer height = 100microns, Infill density = 80%, Printing Speed = 80mm/sec), and according to this test, it can be concluded that a flexural strength of 69.65 MPa has been obtained, which is significantly higher when compared to the highest value of flexural strength obtained from the design of experiments.

6. Future Scope

The work can be extended to analyze other parameters and other mechanical properties such as hardness. The level of experiments can be increased for better results. Further, material consumption can also be minimized to reduce the usage of material so does the cost of the material. The optimization techniques can be changed to Taguchi GRA when there are more than two output parameters.

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