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The Study Focus on Optimizing Processing Parameters for 3D Printed Composites Using Taguchi

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Abstract

The effect of fused filament fabrication (FFF) process parameters on the mechanical properties of 3D-printed carbon fiber (CF)-reinforced recycled polylactic acid (rPLA) composite is presented in this paper. Because they have a significant impact on the mechanical properties of the product layer thickness, raster orientation and infill percentage are the process variables taken into consideration for the studies. The response parameters considered in the study are tensile strength. There is multi-optimisation. Utilizing TOPSIS (Technique for Order Preferences by Similarity to Ideal Solution) analysis to determine the optimal combination of parameters that would yield the greatest strength.

Keywords

FDM, Process Parameters, tensile strength, recycled PLA & rPLA-CF, TOPSIS method.

Introduction

3D Printing technology involves the creation of components by adding material layers in a precise, controllable manner. Over the past three decades, seven basic methods are Powder Bed Fusion, Directed Energy Deposition, Binder Jetting, Sheet Lamination, Material Extrusion, Material Jetting, Vat Photopolymerization have been developed, with over technologies used by various industrial companies. Advantages include accurate building of complex parts, minimal material waste, easy mass customization, and the ability to create objects difficult or impossible by classical methods. Alternative for FDM is fused filament fabrication and also called as material extusion process. Filament is fed through a heated printer extruder head, deposited on layer by layer. The print head moves under computer control to define the printed shape, depositing layer one on another. The speed of the extruder head can be controlled for interrupted planes (Singh & Devi, 2019; Mishra et al., 2023). Fused filament fabrication involves material extrusion, where a feedstock material, typically filament wound onto a spool, is pushed through an extruder. The 3D printer liquefier is a crucial component in this printing process, used in extruders with a cold and hot end. The cold end pulls material, while the hot end contains a heating chamber and nozzle. The liquefier melts the feedstock, forming a plastic bead that adheres to the material, with different nozzles and heating methods (Hiemenz, 2011). The processes involve various types of extruders and different materials to create the final product (Bin Hamzah et al., 2018). The 3D printer head or extruder is a crucial component in additive manufacturing, responsible for melting or softening raw materials like thermoplastics into a continuous profile. 3d printing uses polymers like ABS, PC, PLA (Girish Kumar & Devaki Devi, 2023), HDPE, and PETG as filaments. Fluoropolymers like PTFE tubing are used due to their high temperature resistance, making it ideal for filament transfer (Bin Hamzah et al., 2018). Photopolymers dominate the 3D printing market, focusing on strength in specific mechanical characteristics. This

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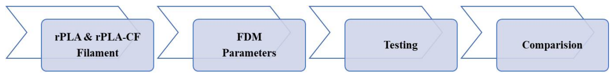
technology can produce parts with superior mechanical, electrical, and thermal properties compared to conventional technologies. PLA materials are a major competitor in the 3D printing industry, offering strength and lightweight parts. Chopped PLA offers cost-effective, thermally resistant, and impact energy absorption alternatives to Titanium, with applications in sports, automobile, and aviation. 3D printing market revenue is predicted to reach $7-23 billion by 2020, a significant increase from the $200 billion injection molded plastic market. PLA, derived from plant materials, can be managed through composting, combustion, recycling, and landfill dumping, with recycling having a significantly lower environmental impact. Recycled PLA, made from corn, has a significantly lower carbon footprint than petroleum-based plastics, as it is produced locally and has a 3000 times lower carbon footprint (Columbus, 2015; Vink et al., 2003; Shen, 2011). To create high-strength, cost-effective 3D-printed parts, saving time in designing designs requiring specific mechanical strength parameters. Recycling 3D printed PLA (Girish Kumar & Devaki Devi, 2024) demonstrating that it can yield parts with similar properties to virgin filament, potentially saving significant costs and emissions (Anderson, 2017). Parameters for producing high-strength 3D-printed parts with minimal material usage for flexural and tensile strength-demanding products and also by using neural networks were found optimal parameters (Girish Kumar & Devaki Devi, 2024). The techniques for better process parameter optimization can be applied to create a high-performing part by utilizing FDM technology throughout the fabrication process. Therefore, optimizing the process parameters is crucial to lowering errors and raising quality. The properties of a composite are influenced by the constituent materials, additives, fillers, and reaction phases, including fiber length, orientation, cross-sectional shape, distribution, and proportions of fiber and matrix material.

Objectives

- To compare the maximum amount of tensile load a material can bear before fracturing of rPLA and rPLA-CF.
- To analyze and compare the mechanical properties of rPLA and rPLA-CF.
- To identify any significant differences of material induced to reduce cost and stability by strength.

Material & Method

The 1.75 mm diameter recycled PLA & PLA-CF filament used as the study's material shown in Fig. 1b & 1c and methodology shown in Figure 1a. This project's novelty is 3D printing with recycled composite material. The Pratham 5.0 was utilized in the specimen's production. The printer (Fig. 2) has a nozzle diameter of 0.4 mm. Product modeling was carried out using Cura Ultimaker, a 3D printing program, and Creo 2016.



(a) Methodology

(b) recycled PLA

(c) recycled PLA-CF

Fig. 1. Recycled PLA & PLA-CF filament used as the study's material

Fig. 2. Pratham 5.0 3D Printer

This study uses ASTM D638 for tensile testing and compression testing to model a specimen for evaluating layer thickness, raster orientation angle and material infill. The quality of produced parts is influenced by the type of machine used. Infrared radiant machines produce higher mechanical properties and filling fraction, but increase yellowing. Closed-loop recycling of ABS for AM increases tensile modulus and strength, but decreases impact strength and melt viscosity. Characterize and optimize the parameters such as layer thickness and PLA build material which is mixed with recycled PLA material layer thickness and PLA build material mixed with recycled PLA material for improved mechanical properties of printed specimens through tensile and flexural tests. Recycled PLA filament for 3D printing and conducted mechanical tests on short-beam strength. Results showed similar short-beam strength to virgin specimens (Dal Fabbro et al., 2021; Babagowda et al., 2018; Lanzotti et al., 2019).An experiment plan was created using the values of the processing parameters given in Tables 1 and 2 to create a total of 9 samples for the tensile and compression, with a layer height, raster orientation and material infill percentage.

Table 1
Optimization of parameters by L9 array

S No	Layer Height (mm)	Orientation (°)	Infill Density (%)
1	0.1	0	30
2	0.2	45	30
3	0.3	90	30
4	0.2	0	60
5	0.3	45	60
6	0.1	90	60
7	0.3	0	90
8	0.1	45	90
9	0.2	90	90

The process parameter that is the subject of attention for that specific sample is indicated by the values in bold. As indicated in Table 1, each of these processing parameters was examined on a 3-level.

A technique for handling decisions with multiple criteria is TOPSIS (technique for order preferences by similarity to ideal solution. TOPSIS shown in below flow chart analysis evaluates alternatives by measuring distances to the positive and negative ideal solutions, ranking process parameters from highest to lowest (Castanon-Jano et al, 2023; Büth et al., 2020; Saputra et al., 2023).

The parts were modeled using creo 2016 and transferred to Cura Ultimaker in .stl format, and fabricated using a Pratham 5.0 3D printer and process parameter selected to print the specimen by using below Table 1 selected parameters.

Table 2
Tensile Strength & Elongation % results

Specimen	rPLA Tensile Strength (MPa)	rPLA-CF Tensile Strength (MPa)	rPLA Elongation (%)	rPLA-CF Elongation (%)
L1	13.48	27.67	3.5	**3.2**
L2	16.27	31.65	**3.8**	5.2
L3	15.19	32.78	2.1	4.7
L4	26.47	39.02	3.6	4.9
L5	27.56	40.18	3.7	5.4
L6	19.64	43.18	**1.8**	5.0
L7	23.21	45.35	3.4	5.5
L8	21.45	49.36	2.6	**5.5**
L9	**29.73**	**51.85**	3.4	5.2

Normalized Matrix: $\sqrt{\sum_{j=1}^{n} X_{ij}^2}$

↓

Weight Normalized Matrix: $W_{jx} = \dfrac{X_{ij}^2}{\sqrt{\sum_{j=1}^{n} X_{ij}^2}}$

↓

Ideal Best Solution: $S_i^+ = \left[\sum_{j=1}^{m} (V_{ij} - V_j^+)^2\right]^{0.5}$

↓

Ideal Worst Solution: $S_i^+ = \left[\sum_{j=1}^{m} (V_{ij} - V_j^-)^2\right]^{0.5}$

↓

Performance Score: $P_i = \dfrac{S_i^-}{S_i^+ + S_i^-}$

Flow chart 1: TOPSIS METHOD

Results

After testing on UTM the strength of samples and elongation are shown in Table 3.

From the Table 2 For recycled polylactic acid, Sample (L9) got higher tensile strength of 29.73 MPa and (L1) got lowest tensile strength of 13.48 MPa and for rPLA-CF, sample (L3) 52.61 MPa and sample (L4) got lowest strength of 27.67 MPa. After keen observation of results.

For rPLA all the parameters (30%, 60% & 90% infill density, 0°, 45° & 90° orientation and 0.1, 0.2 &

0.3 mm layer thickness) got brittle property but the sample L6 (infill density 60 %, orientation 90° and layer height 0.1mm) got 1.8 elongation % from this it is clear that given polymer is brittle.

For rPLA-CF only the parameter (30% and 60% infill density, 0° and 90° orientation and 0.1, 0.2 & 0.3 mm layer thickness) got brittle whereas (90% infill, 45° orientation) got ductility property, from all the samples, L1 (infill density 30%, orientation 0° and layer height 0.1mm) got 3.2% elongation and component print with the given parameters got brittle in nature.

From the Table 3 it is concluded that the best combination for rPLA is A2,B2,C3 and for rPLA-CF A1B3C1 gives an optimal strength based on Signal to Noise Ratio. According the main effects plot for SN ratios as shown in Fig. 3a & 3b, for rPLA it concludes that 0.2 mm Layer height, 45° orientation and 90% infill density give maximum strength occurred and for rPLA CF 0.1 mm Layer Height, 90° orientation and 30% infill density got high strength.

Based on the Table 4 the elongation percentage of the specimen. The load applied on the specimen, after enlargement of the both ends, elongation accur here in the above table effects of the S/N raio of Elongation % variation of specimens made by different combination of parameters. By table the best combination for rPLA is A2, B1, C3 and for rPLA-CF A3B2C3.

Table 3
Response Table for Signal to Noise Ratios for Tensile Strength

	Tensile Strength rPLA			Tensile Strength rPLA-CF		
Level	LH	Ori	ID	LH	Ori	ID
1	25.03	26.12	23.48	32.34	31.27	33.17
2	27.38	26.55	27.71	31.21	30.80	31.01
3	26.58	26.32	27.80	32.14	33.62	31.51
Delta	2.35	0.43	4.32	1.13	2.82	2.16
Rank	2	3	1	3	1	2

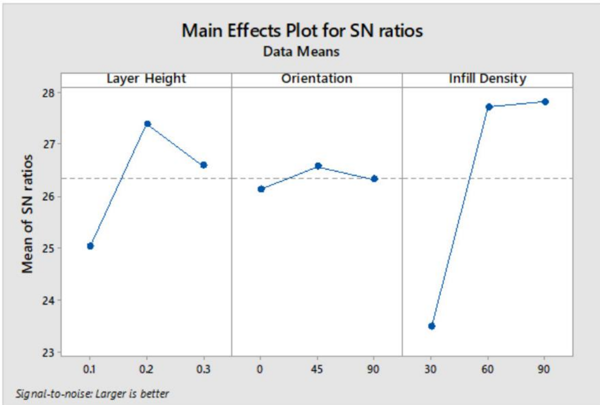
Table 4
Response for Signal to Noise Ratios for Elongation (%)

	Elongation (% rPLA)			Elongation (% rPLA-CF)		
Level	LH	Ori	ID	LH	Ori	ID
1	8.146	10.895	9.727	12.96	12.87	12.57
2	11.090	10.436	9.278	14.11	14.55	14.06
3	9.557	7.461	9.788	14.23	13.87	14.67
Delta	2.945	3.434	0.510	1.27	1.68	2.09
Rank	2	1	3	3	2	1

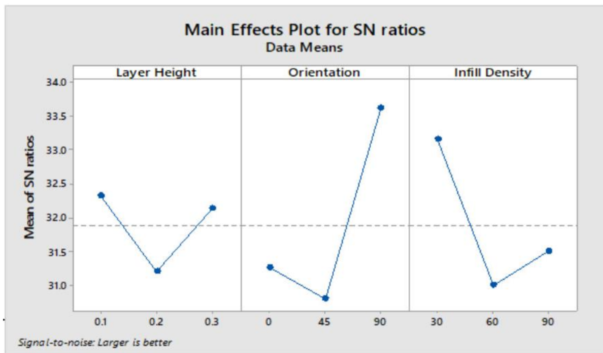
According the main effects plot for SN ratios as shown in Fig. 4a & 4b, for rPLA concludes that 0.2 mm Layer height, 0° orientation and 90% infill and for rPLA CF 0.3 mm Layer Height, 45° orientation and 90% infill density got higher elongation at break percentage have higher ductility.

Higher layer thickness indicates less layers in the component, while a lower layer thickness indicates more layers in the component and also affect the tensile strength, time to print the part and its surface smoothness. The study indicates that increasing the layer height improves tensile strength, suggesting that having fewer layers leads to more durable printed parts. From the table Highest strength got 0.2 mm for rPLA and 0.3 mm for rPLA-CF shown in Graph 1&2.

From above graph it is observer that the direction of flow the filament in the component, considered three horizontals (0°), inclined (45°) and vertical (90°). The 90° orientation demonstrated the highest strength in the tensile test as shown in Graph 3, while horizontal and inclined layers showed weaker interaction due to weaker molecular bonding shown in Graph 4.

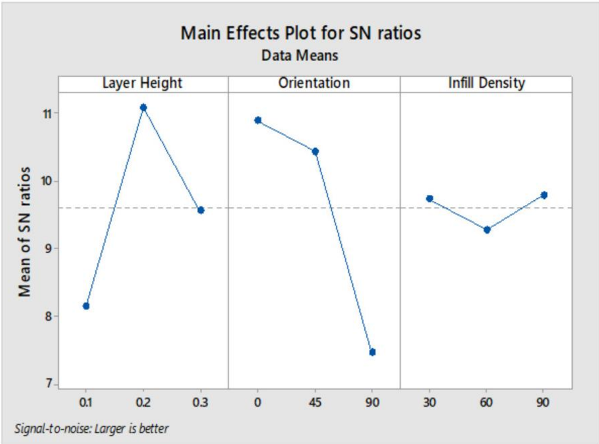


(a) rPLA

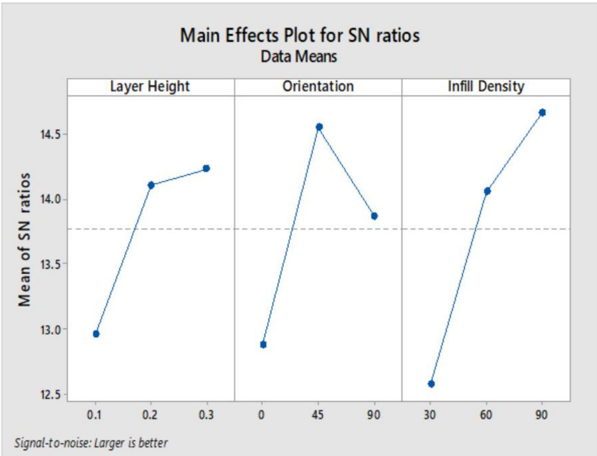


(b) rPLA-CF

Fig. 3. S/N ration for Tensile Strength

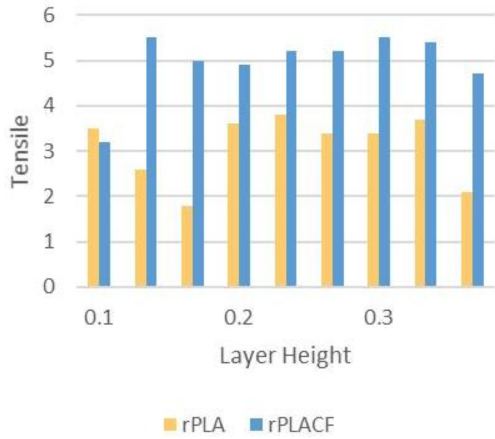


(a) rPLA

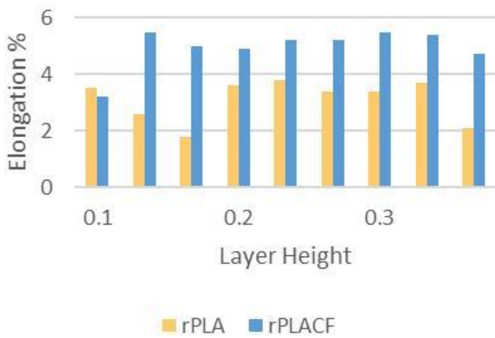


(b) rPLA-CF

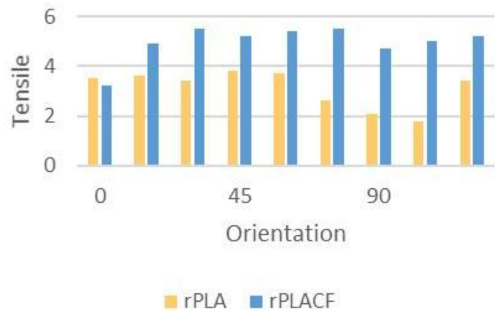
Fig. 4. S/N ration for Elongation %



Graph 1: Tensile vs Layer height



Graph 2: Elongation vs Layer height



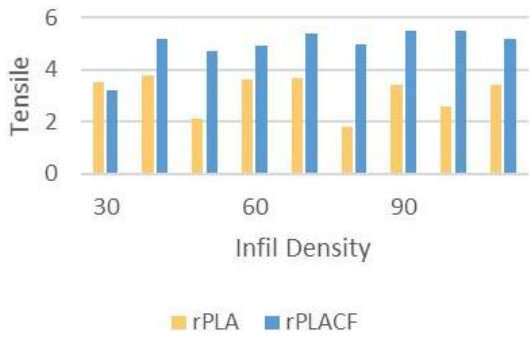
Graph 3: Tensile vs Orientation

Graph 4: Elongation vs Orientation

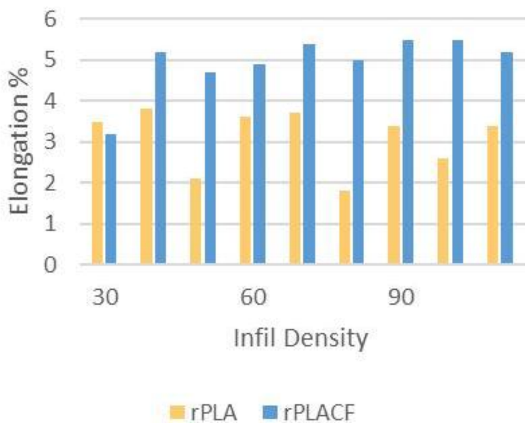
From the observation, higher infill percentages significantly enhance tensile strength by providing more material to bear the applied load on the component/part, but here from the study it is clear that for composite rPLA-CF lesser infill density also got good strength. From table 60% and 90% infill got high tensile strength for rPLA-CF and elongation also for less infill percentage shown in Graph 5&6.

From TOPSIS analysis ranked specimens based on strength, with the strongest being ranked first. This helps determine the optimal printing parameter values, as shown in Table 5 The TOPSIS method ranked specimen number 9 as the strongest, with 90% infill, 90° orientation and 0.2 mm layer height, indicating that infill percentage was the most significant factor affecting tensile strength.

From the Table 6 specimen 9 got elongation rank for both recycle PLA and recycled PLA-CF.



Graph 5: Tensile vs Infill Density



Graph 6: Elongation vs Infill Density

Table 5
rPLA & rPLA-CF Specimens were ranked based on tensile strength using TOPSIS

	rPLA Tensile (MPa)				rPLA-CF Tensile (MPa)			
Sample No	Si+	Si-	Pi	Rank	Si+	Si-	Pi	Rank
1	0.18	0.00	0.00	9	0.17	0.04	0.26	9
2	0.10	0.14	0.58	3	0.08	0.15	0.65	2
3	0.12	0.07	0.38	8	0.11	0.08	0.45	7
4	0.09	0.13	0.57	4	0.09	0.14	0.62	3
5	0.10	0.11	0.51	5	0.11	0.11	0.53	5
6	0.12	0.12	0.50	6	0.12	0.12	0.43	6
7	0.13	0.08	0.37	7	0.14	0.06	0.25	8
8	0.07	0.12	0.61	2	0.08	0.11	0.59	4
9	0.03	0.17	0.81	1	0.04	0.16	0.71	1

Table 6
rPLA & rPLA-CF Specimens were ranked based on Compression strength using TOPSIS

	rPLA Elongation (MPa)				rPLA-CF Elongation (MPa)			
Sample No	Si+	Si-	Pi	Rank	Si+	Si-	Pi	Rank
1	0.17	0.04	0.20	9	0.17	0.00	0.00	9
2	0.10	0.14	0.59	3	0.08	0.14	0.62	2
3	0.11	0.09	0.45	7	0.11	0.08	0.42	7
4	0.10	0.13	0.55	4	0.09	0.13	0.59	4
5	0.10	0.11	0.50	5	0.10	0.11	0.53	5
6	0.12	0.12	0.50	6	0.12	0.12	0.50	6
7	0.13	0.07	0.36	8	0.13	0.06	0.33	8
8	0.07	0.12	0.61	2	0.07	0.11	0.60	3
9	0.04	0.16	0.79	1	0.04	0.16	0.80	1

Conclusion

The paper investigates the impact of FDM process parameters on part characteristics, focusing on infill percentage, orientation, and layer height independently, resulting in the following conclusions. The study aimed to identify the optimal parametric values for 3D-printed products requiring strength in tensile characteristics, revealing that orientation doesn't significantly tensile strength, but layer height and infill percentage significantly do. The maximum tensile strength was attained with a layer height of 0.2 mm, infill percentage of 90% and 90° orientation when compare with TOPSIS method and it recommends also with a parameter of 90% infill, 0.2 mm layer height, and 90° orientation for optimal tensile strength results are validated.

Future scope

Future research will explore various process parameters like infill pattern, temperature, and nozzle diameter to minimize mechanical properties loss in FDM printed components.

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