Arch. Metall. Mater. **70** (2025), 1, 97-104

DOI: https://doi.org/10.24425/amm.2025.152523

GIRISH KUMAR PVR[1,2*], K. DEVAKI DEVI[3]

INFLUENCE OF MANUFACTURING PARAMETERS ON THE PROPERTIES OF 3D PRINTED POLYLACTIC ACID CARBON FIBER COMPONENTS

This study investigates the impact of printing parameters on fused filament fabrication parts using Polylactic acid and polylactic acid carbon fibre filament. It aims to determine the ideal conditions for 3dprinter to increase the strength of these materials. The study uses to find the effects of infill density, orientation, and layer height on the mechanical characteristics of the materials. Polylactic acid Carbon Fiber is found to be more rigid and have higher tensile strength than Polylactic acid. The most significant parameter influencing results is polylactic acid, despite its more apparent effect. The study suggests that the manufacturing parameters to print the part and can result in higher polylactic acid carbon fibre strength than polylactic acid filament, providing valuable insights for model design and manufacturing. Infill density impact less compare to other two parameter of layer height and orientation. Compare to polylactic acid composite polylactic acid carbon fibre influence the parameters to increase of strength.

Keywords: Polylactic acid filament; polylactic acid carbonfiber filament; Fused deposition modelling; Tensile; SEM

1. Introduction

Fused deposition modeling (FDM) is a key technology in Industry 4.0 for creating sustainable engineering products and biomedical devices. However, 3D-printed parts' mechanical strength and durability remain lower than conventional ones. Its thermoplastic composite structures are prepared using FDM technology and discuss additives that enhance overall quality [1]. By incorporating reinforcing materials like short glass fibers into the thermoplastic matrix, the mechanical properties of the composite filaments are improved [2]. And, materials like short glass fibers the mechanical properties of recycled high-density polyethylene and recycled polyethylene terephthalate blend thermoplastic composite filaments are enhanced [3]. CNT/PLA printed films have excellent electromagnetic shielding and low-voltage electric heating properties, enhancing the application potential of EMI shielding materials [4]. The addition of oil palm fiber improves thermal stability, intermolecular hydrogen bonding, and moisture resistance. The 7 wt% oil palm fiber composite shows better dimension stability than 3 and 5 wt% [5]. Brass-filled polylactic acid specimens have the highest flexural strength and modulus, while tungsten is the most wear-resistant filler [6]. The highest strength was achieved with CarbonPLA + PLA white and Bronze + PLA white composites in the length direction. Strength values decreased significantly when printed perpendicular to the applied force, reaching 10% of the strength of samples printed in the direction of stress force. Influence of printing orientation on 3D printed samples, with CarbonPLA material showing 10 times higher tensile strength when printed in length. Part orientation and load type are crucial in printing reinforced PLA parts. Most tested materials show low elongation and plastic deformation, with only PLA Carbon material experiencing good plasticity [7]. The increasing demand for carbon fibers due to their high-temperature resistance, mechanical characteristics, and lower price has led to the development of carbon-fiber-reinforced polymers or plastics [8]. DSC curves revealed higher crystallinity in the PLA-CF specimen, with an agglomeration of carbon fibers. XRD patterns showed a non-crystalline to α-crystalline structure, while the diffraction peak widened. Carbon fiber incorporated reduced tensile strength increased Young's modulus, and elongation-at-break [9]. CFP-reinforced PLA composites, finding improved tensile and joint strengths, PEO addition, weak fiber-PLA matrix adhesion, and higher joint failure loads than PLA/PEO composites [10]. polylactic acid/carbon fiber composites using fused deposition modeling, focusing on impact, tensile, and flexural strength,

1 RESEARCH SCHOLAR, JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY ANANTAPUR, DEPARTMENT OF MECHANICAL ENGINEERING, AP, INDIA
2 SENIOR ASSISTANT PROFESSOR, GEETHANJALI COLLEGE OF ENGINEERING AND TECHNOLOGY, DEPARTMENT OF MECHANICAL ENGINEERING, HYDERABAD, TS, 501301 INDIA
3 ASSOCIATE PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING, G. PULLA REDDY ENGINEERING COLLEGE, KURNOOL, AP, INDIA

* Corresponding author: girishkumarpvr@gmail.com

Fig. 1. Methodology

and examining fracture mechanisms [11]. PLA/CFRC, which has potential applications in prosthetic implants. FTIR analysis reveals chemical interactions between PLA and CFRC, and the composite's thermal behavior. It has cell viability above 80%, tensile modulus, and strength, like bone, making it a promising base material for hip femoral stem prostheses [12].

3D printing technology is revolutionizing the manufacturing industry, with carbon fiber-reinforced PLA being a popular material. However, research on optimizing process parameters for Fused Deposition Modelling (FDM) printed PLA-CF is limited.

This study uses the Taguchi design of the experiment approach to determine optimal parameters to find the mechanical properties and the methodology shown in Fig 1.

2. Experimentation

Creo is used to create the model shown in Fig. 2 shows dimensions 2D and 3D model as per the standards ASTM D 638 (TYPE 1) SPECIMEN DIMENSIONS mentioned in TABLE 1 below.

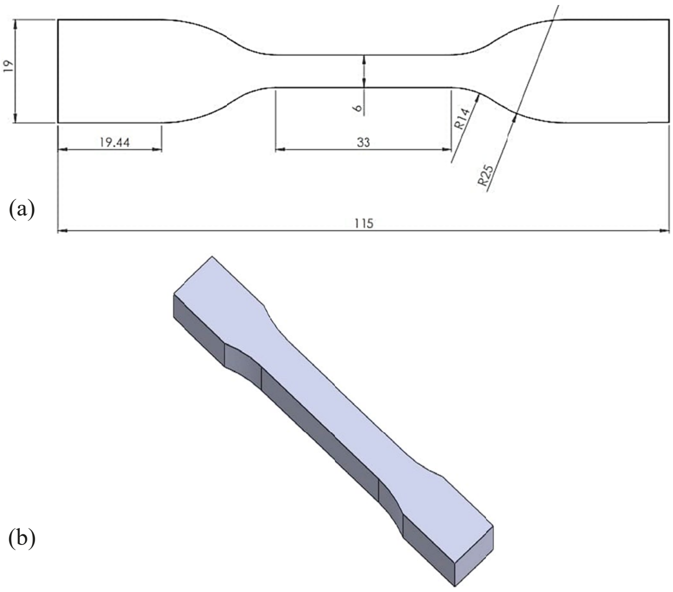

Fig. 2. ASTM D638 Type IV: (a) 2D & (b) 3D

In this project, there is a total of 3 parameters. They are infill density, orientation and layer height. And for every parameter, there is a total of 3 values. They are one low value, intermediate value and the last one is high value. So, there are 3 factors and 3 levels. By using the Minitab software, we minimize the optimization of the design into L9 Array are shown in below TABLE 1.

3D printing, or additive manufacturing, involves stacking materials under computer control to create three-dimensional objects. It involves creating a 3D model, choosing a material, setting up a printer, printing, post-processing, and quality control. The procedure may vary depending on the printer, method, and material.

TABLE 1

Optimization of parameters by L9 array

S. No	Layer Height (microns µm)	Orientation (angle °)	Infill Density (percentage %)
1	120	0	20
2	180	45	20
3	300	90	20
4	180	0	60
5	300	45	60
6	120	90	60
7	300	0	80
8	120	45	80
9	180	90	80

FDM technology Make3D Pratham 5.0 3D printer shown in Fig. 3 creates 3D objects by building layers of material, with thermoplastic filament deposited in each layer and specifications shown in TABLE 2. This additive manufacturing method is clean, simple, and office-friendly, using mechanically and environmentally stable materials like thermoplastics. Stratasys FDM technology enables complex geometries and parts with internal cavities, providing precise tolerances, durability, and stability in various environments. Using an Pratham 5.0-3D printer, the sample is printed on the bed, and all the printed specimens are tested and specimens are shown in Fig. 4.

Fig. 3. Pratham 5.0 3D printer

Fig. 4. Samples after testing

TABLE 2

3D Printer Specifications

Company/ Country	Pratham 5.0/Make3D
Technology	Fused Deposition Modelling (FDM)
Build volume	500 mm*500 mm*500 mm
Nozzle	Single Extruder
Materials used	PLA, TOUGH PLA, PLACF

3. Result and discussion

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

TABLE 3

Tensile Strength & Elongation % results

Specimen	PLA Tensile Strength MPa	PLACF Tensile Strength MPa	PLA Elongation %	PLACF Elongation %
L1	14.58	46.42	3.53	3.2
L2	17.07	39.08	3.81	5.15
L3	16.09	52.61	2.14	4.65
L4	25.67	28.87	3.6	4.85
L5	27.14	31.89	3.74	5.35
L6	18.52	48.45	1.83	4.95
L7	24.31	40.22	3.39	5.48
L8	20.36	30.15	2.58	5.53
L9	28.93	42.48	3.36	5.23

For PLA, Sample (L9) infill density 80%, orientation 90° and layer height 0.18 mm got higher tensile strength of 28.93 MPa and (L1) infill density 20%, orientation 0° and layer height 0.12 mm got lowest tensile strength of 14.58 MPa.

For PLA-CF, sample (L3) infill density 20%, orientation 90° and layer height 0.3 mm got higher strength of 52.61 MPa and Sample L4 got infill density 60%, orientation 0° and layer height 0.18 mm lowest strength of 28.87 MPa.

Thermosetting polymers are often strong and hard, although they are also frequently brittle. The percentage elongation measures ductility, while the percentage reduction in area, calculated as the reduction in cross-sectional area of a tensile specimen at fracture, is also a measure of ductility. If the percentage of elongation is greater than 5%, the material is considered ductile; if it is less than 5%, the material is considered brittle. From the TABLE 3 all the samples of PLA got <5% whereas for PLACF samples L2, L5, L7, L8 and L9 got >5% elongation so they are all toughness but L1, L3, L4 & L6 elongation got <5%.

After keen observation of results

For PLA all the parameters (20%, 60% & 80% infill density, 0°, 45° & 90° orientation and 0.12, 0.18 & 0.3 mm layer thickness) got brittle property but the sample L6 (infill density 60%, orientation 90° and layer height 0.12 mm) got 1.83 elongation % from this it is clear that given polymer is brittle.

For PLACF only the parameter (20% and 60% infill density, 0° and 90° orientation and 0.12, 0.18 & 0.3-mm layer thickness) got brittle whereas (80% infill, 45° orientation) got ductility property, from all the samples, L1 (infill density 20%, orientation 0° and layer height 0.12 mm) got 3.2% elongation and component print with the given parameters got brittle in nature.

From the TABLE 4 it is concluded that the best combination for PLA is A2,B1,C3 and for PLACF A3B2C3 gives an optimal strength based on Signal to Noise Ratio.

TABLE 4

Response Table for Signal to Noise Ratios for Tensile Strength

Level	Tensile Strength PLA			Tensile Strength PLACF		
	Layer Height	Orientation	Infill Density	Layer Height	Orientation	Infill Density
1	24.93	26.39	24.02	32.21	31.54	33.20
2	27.35	26.50	27.40	31.20	30.50	31.00
3	26.84	26.24	27.71	32.19	33.56	31.41
Delta	2.42	0.26	3.69	1.00	3.06	2.20
Rank	2	3	1	3	1	2

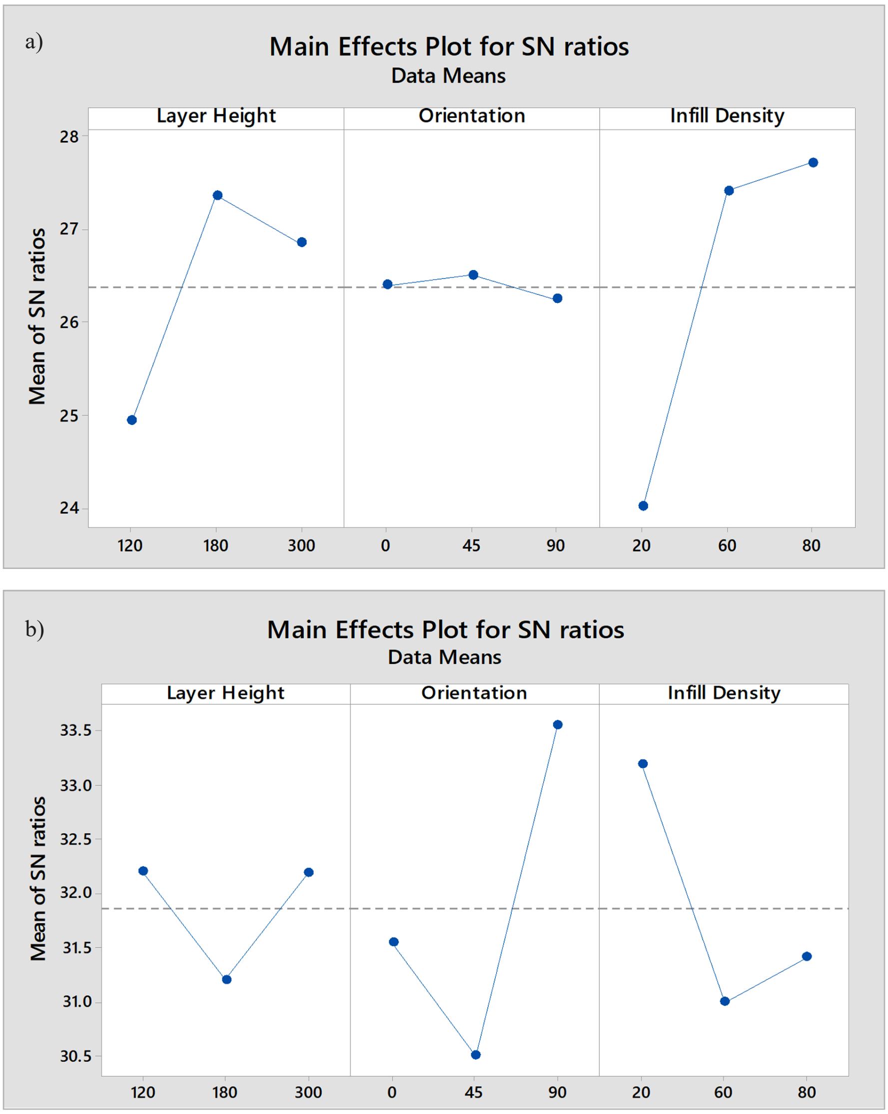

Fig. 5. S/N ration effect plots for Tensile Strength a) PLA b) PLACF

According the main effects plot for SN ratios as shown in Fig. 5, for PLA it concludes that 0.18 mm Layer height, 45° orientation and 80% infill density give maximum strength occurred and for PLA CF 0.12 Layer Height, 90° orientation and 20% infill density got high strength.

TABLE 5

Response Table for Signal to Noise Ratios for Elongation %

Level	Elongation % PLA			Elongation % PLACF		
	Layer Height	Orien-tation	Infill Density	Layer Height	Orien-tation	Infill Density
1	–8.146	–10.895	–9.727	–12.95	–12.86	–12.56
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	1.28	1.69	2.10
Rank	2	1	3	3	2	1

Based on the above TABLE 5 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 PLA is A2,B2,C3 and for PLACF A3B3C1.

According the main effects plot for SN ratios as shown in Fig. 6, for PLA it concludes that 0.12 mm Layer height, 90° orientation and 60% infill density give maximum strength occurred and for PLA CF 0.12 mm Layer Height 0° orientation and 20% infill density got high strength. From the above observation the tensile strength of PLACF is higher compare to PLA.

ANNOVA is used to determine the effects of process responses. From the above TABLE 6 it concludes for both materials P-Value got <0.05 hence the parameter is significant and rest of other two parameters are not significant because the P-value got >0.05. Comparing the outcomes of the ANNOVA results it concluded that Orientation 45° & 90° is significant compare to other and also suggested that orientation is the parameter which also impacts on the model stiffness more over after printing the surface of the model tested compare of all 9 models the L2 got lesser R_a value of 2.95 which got good surface finish for PLA where as for PLA CF L3 got R_a value of 6.028 got good surface

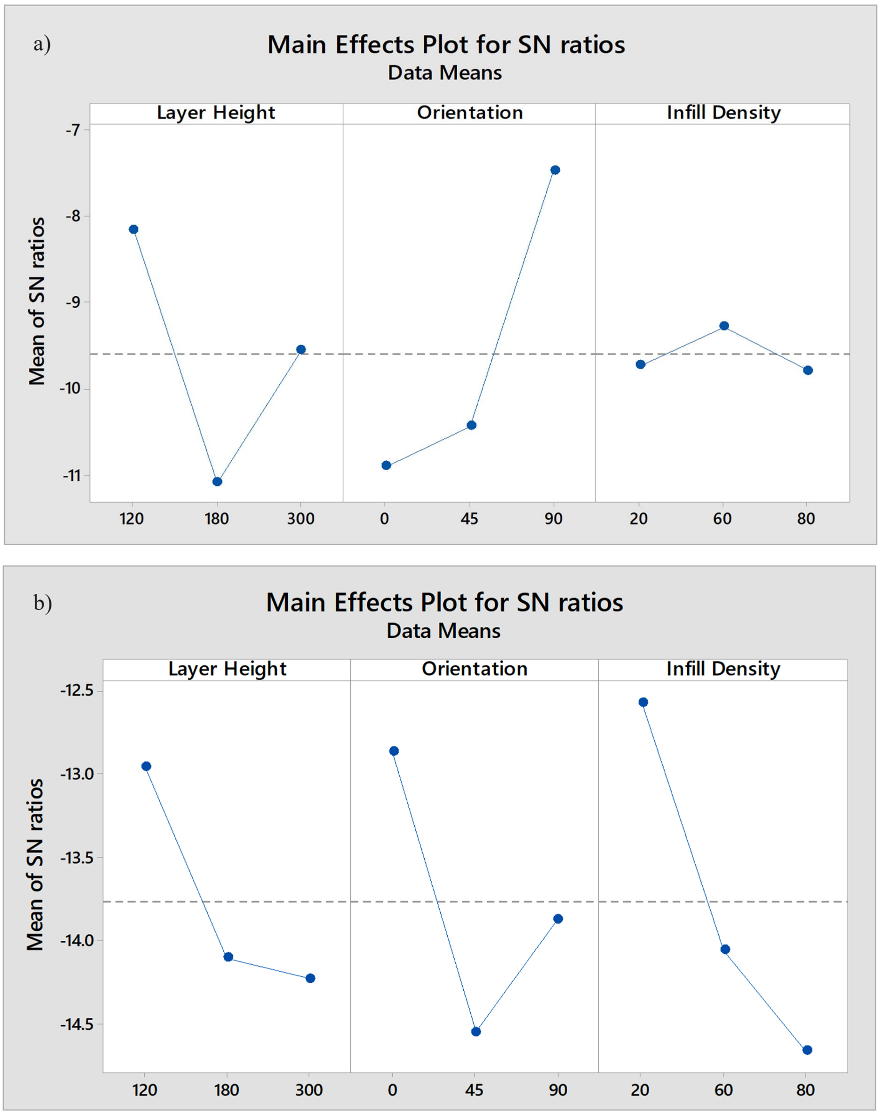

Fig. 6. S/N ration effect plots for Elongation % a) PLA b) PLACF

TABLE 6

Analysis of Variance

Source	PLA				PLA-CF			
	Adj SS	Adj MS	F-Value	P-Value	Adj SS	Adj MS	F-Value	P-Value
Regression	762.0	254.00	5.49	0.049	67.36	22.452	5.72	0.045
Infill Density	138.7	138.68	3.00	0.144	15.63	15.632	3.98	0.103
Orientation	520.1	520.06	11.25	0.020	39.17	39.168	9.97	0.025
Layer Height	103.3	103.27	2.23	0.195	12.56	12.557	3.20	0.134
Error	231.2	46.23			19.63	3.927		
Total	993.18				86.99			

finish and in this both the process parameter layer height 0.18 mm is common and efficient/prominent parameter to print the model.

Surface quality is low, with strong corrugated outer layers and pore-free undersides. Undersides are smooth, while upper surfaces have comparable, sometimes need support materials, such as water or chemicals like limonene, which significantly improves the quality of surfaces in areas with support material. Finishing for PLA typically consists of removing the support material but here in this there is no support material and tested on upper portion of the specimen and results are displayed in TABLE 8.

The study examined that for both PLA & PLACF the impact of orientation (0°, 45°, 90°) on surface roughness in 3D printed samples, finding that variations in layer thickness affected surface roughness, but infill density and layer thickness had a lower significant effect.

According to hardness, possible Shore durometer type D is used and values of polymer range is 0-80. From the table,

TABLE 7

Surface Roughness and Hardness

Specimen	PLA Surface Roughness R_a	PLA Hardness	PLA-CF Surface Roughness R_a	PLA-CF Hardness
L1	3.99	48	7.199	73.5
L2	2.95	27	6.549	67.6
L3	10.24	67	9.613	54.3
L4	4.06	50	6.028	79.6
L5	3.98	51	7.902	78.3
L6	17.02	42	6.146	75.7
L7	5.17	43	7.857	79.6
L8	3.75	32	6.686	75.5
L9	15.39	52	6.317	75.0

it is concluded that all the specimens are under 80 range only upon them the for PLA L3 and PLACF L7 got good values, comparing L3 & L7 layer thickness is the important with increasing of layer height hardness also increases.

TABLE 8

Experimental vs Predicted results

Property	Tensile Strength		Elongation %	
	PLA	PLA-CF	PLA	PLA-CF
Experimental	28.93	52.61	1.83	3.2
Predict	28.80	55.5189	–5.68940	–10.8521
Difference	0.44	5.51	2.1	2.3

Compare with previous PLA SEM images [14,15]. SEM analysis of carbon fiber reinforced polymer (CFRP) specimen before and after tensile tests revealed intrinsic manufacturing defects affecting mechanical properties. Debonding occurs when physical, chemical, or mechanical forces break, leading to delamination in laminated materials, often composites, causing separation of reinforcement layers. In the above Fig. 7, can see there is porosity formed in between the layers. Porosity results may the specimen being a failure compared with other papers. In Fig. 8 which obtained the highest Ultimate Tensile Strength

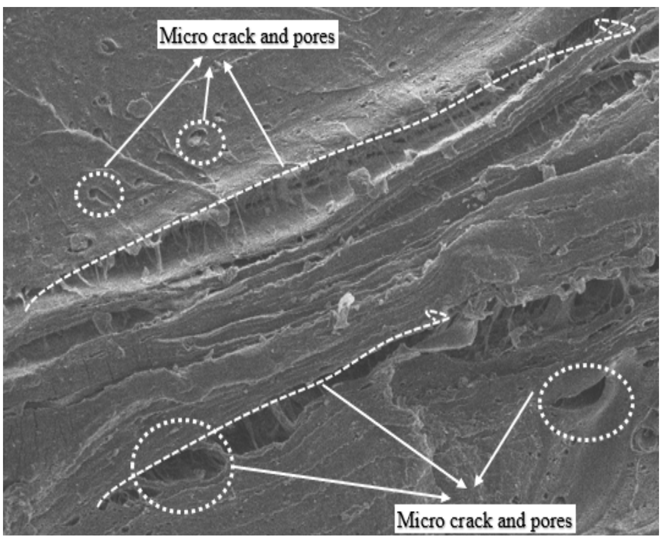

Fig. 7. Porosity

among all the specimens. In this can see the elongation of the carbon fibres blended with PLA. The circled part of the image shows the elongation of the fibers. In the above Fig. 9, we can see the layer-by-layer bond of the specimen.

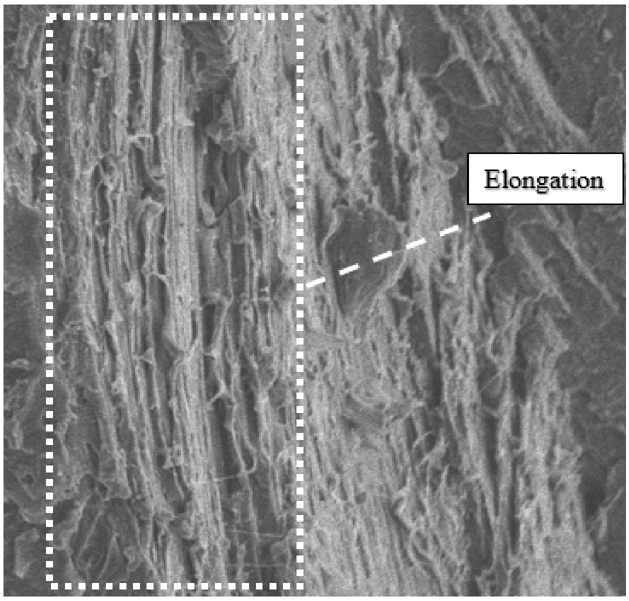

Fig. 8. Elongation

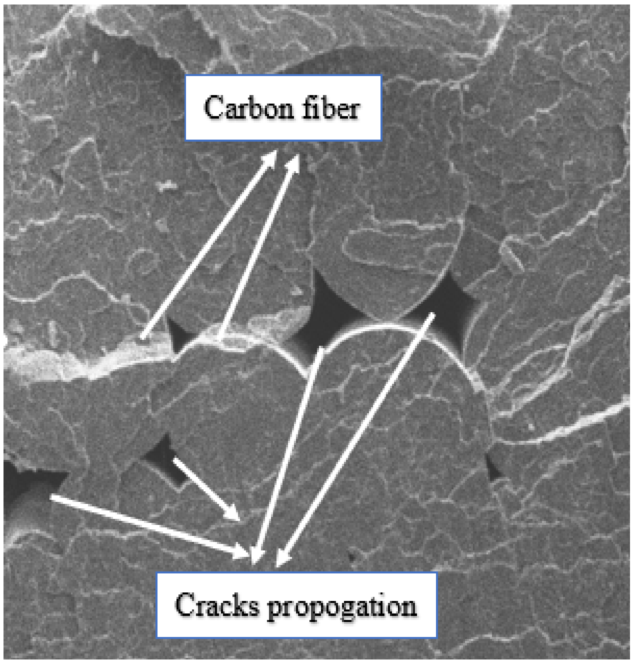

Fig. 9. Carbon fibre

For the purpose of determining the precision of the mechanical and sustainability features of sample components, the suggested technique is compared to the DOE method and the lab testing solution, as indicated in Table. The suggested technique is compared to the DOE method and experimental to determine the precision of mechanical and sustainability of sample components. From the TABLE 8 it concluded that the values are predicted precisely when compare with experimental results the most significant difference between experimental and optimization method solutions is for PLA 0.44% & 2.1%, for PLACF 5.51% & 2.3%.

The researchers focus on optimizing machine parameters for 3D printing carbon fiber reinforced PLA thermoplastics, achieving a tensile strength with infill density, print speed, and layer height, useful for various applications and PLA components with varying infill percentages, raster angles, and layer thickness, revealing good compression, flexural, and microstructural behavior, reducing material deposition and printing sample time. Highest average tensile strength of 48.886 MPa, with good adhesion between printed layers, confirming good adhesion through fracture analysis [16]. Nozzle temperature and infill density significantly impact the tensile properties of FDM printed PLA products, with optimal processing parameters at 220°C and 100% infill density [17] and impact of nozzle temperature and infill line orientations on the tensile properties of parts made with short carbon fiber-reinforced polylactic acid [18]. Knowledge distillation reduces predictive model complexity and computational load in additive manufacturing. KD-based predictive model with geometry-based features has the lowest RMSE, MAE, training time [19] and neural network [20].

4. Conclusion

As discussed earlier, parameter variation has a huge influence on 3D-printed parts. Specimens that we produced on FDM technology with PLA-CF material Showed a drastic positive variation in mechanical properties. In this study, the impact of PLA and PLACF material orientation & layer height, two key FDM process factors, was first thoroughly examined. A tensile test was also conducted. L9 orthogonal array of three variables and three levels was used to analyze the impact of printing with orientation and layer height on tensile, surface and hardness characteristics. The analysis showed that orientation would yield the best tensile strength combination. The ideal tensile strength of the above-mentioned is PLA 28.93 MPa & PLACF 52.61 MPa. Orientation is high impact on tensile strength and elongation percentage whereas for surface finish and hardness layer height is high impact. The primary factor impacting the tensile strength of FDM specimens is the orientation and layer height is the secondary process parameter. The Taguchi s/n ratio analysis was used to identify the optimal parameter level combination for all responses. The ANNOVA and P-value analysis are utilized to identify significant parameter to the responses. The results of taguchi and experimental are well matched. The method is influenced by the simulation and experiment process used to assess the effect of process parameters.

Future Scope

Future work will focus on conducting different process parameters like infill pattern, support structures, support structures pattern, and different diameters of nozzles to minimize the loss of mechanical properties in the FDM printed components.

REFERENCES

[1] V. Mishra, S. Negi, S. Kar, FDM-based additive manufacturing of recycled thermoplastics and associated composites. Journal of Material Cycles and Waste Management **25** (2), 758-84 (2023).

[2] S. Sharma, V. Gupta, D. Mudgal, V. Srivastava, Predicting biomechanical properties of additively manufactured polydopamine coated poly lactic acid bone plates using deep learning. Engineering Applications of Artificial Intelligence **1**, 124, 106587 (2023).

[3] D. Ayane, Development and Characterization of Short Glass Fiber Reinforced-Waste Plastic Composite Filaments for 3d Printing Applications. Available at SSRN 4459139 (2023).

[4] L. Yang, X. Liu, Y. Xiao, B. Liu, Z. Xue, Y. Wang, Additive manufacturing of carbon nanotube/polylactic acid films with efficient electromagnetic interference shielding and electrical heating performance via fused deposition modeling. Synthetic Metals **1**, 293, 117258 (2023).

[5] M. Cao, T. Cui, Y. Yue, C. Li, X. Guo, X. Jia, B. Wang, Investigation of carbon fiber on the tensile property of FDM-produced PLA specimen. Polymers **1**, 14 (23), 5230 (2022).

[6] M.N. Ahmad, M.R. Ishak, M.M. Taha, F. Mustapha, Z. Leman, Mechanical, thermal and physical characteristics of oil palm (Elaeis Guineensis) fiber reinforced thermoplastic composites for FDM–Type 3D printer. Polymer Testing **1**, 120, 107972 (2023).

[7] P. Yaman, O. Ekşi, S.S. Karabeyoğlu, K. Feratoğlu, Effect of build orientation on tribological and flexural properties of FDM-printed composite PLA parts. Journal of Reinforced Plastics and Composite **14**, 07316844231157790 (2023).

[8] E. Spišák, E. Nováková-Marcinčínová, Ľ. Nováková-Marcinčínová, J. Majerníková, P. Mulidrán, Investigation of the Manufacturing Orientation Impact on the Mechanical Properties of Composite Fiber-Reinforced Polymer Elements in the Fused Filament Fabrication Process. Polymers **21**, 15 (13), 2757 (2023).

[9] S. Al Zahmi, S. Alhammadi, A. El Hassan, W. Ahmed, Carbon fiber/PLA recycled composite. Polymers **28**, 14 (11), 2194 (2022).

[10] Ö. Öz, F.H. Öztürk, C. Güleç, Effect of fiber content and plasticizer on mechanical and joint properties of carbon fiber powder reinforced PLA manufactured by 3D printing process. Journal of Adhesion Science and Technology **3**, 37 (15), 2208-31 (2023).

[11] K.R. Kumar, V. Mohanavel, K. Kiran, Mechanical properties and characterization of polylactic acid/carbon fiber composite fabricated by fused deposition modeling. Journal of Materials Engineering and Performance **31** (6), 4877-86 (2022).

[12] M.Á. Caminero, J.M. Chacón, E. García-Plaza, P.J. Núñez, J.M. Reverte, J.P. Becar, Additive manufacturing of PLA-based composites using fused filament fabrication: Effect of graphene nanoplatelet reinforcement on mechanical properties, dimensional accuracy and texture. Polymers **4**, 11 (5), 799 (2019).

[13] J.M. Reverte, M.Á. Caminero, J.M. Chacón, E. García-Plaza, P.J. Núñez, J.P. Becar, Mechanical and geometric performance of PLA-based polymer composites processed by the fused filament fabrication additive manufacturing technique. Materials **19**, 13 (8), 1924 (2020).

[14] P.G. Kumar, Impact of compression and bending behavior on fused deposition modeling of 3D printed components. Materials Today: Proceedings. Apr 21 (2023).

[15] Z Zakaria, M.S. Islam, A. Hassan, M.K. Mohamad Haafiz, R. Arjmandi, I.M. Inuwa, M. Hasan, Mechanical properties and morphological characterization of PLA/chitosan/epoxidized natural rubber composites. Advances in Materials Science and Engineering **1**, 2013 (2023).

[16] J. Singh, K.K. Goyal, R. Sharma, Impact of FDM variables on the tensile property of 3D printed CF-PLA parts. Materials Today: Proceedings. July 28 (2023).

[17] N. Maguluri G. Suresh, K.V. Rao, Assessing the effect of FDM processing parameters on mechanical properties of PLA parts using Taguchi method. Journal of Thermoplastic Composite Materials **36** (4), 1472-88 (2023).

[18] A.E. Magri, K. El Mabrouk, S. Vaudreuil, M.E. Touhami, Mechanical properties of CF-reinforced PLA parts manufactured by fused deposition modeling. Journal of Thermoplastic Composite Materials **34** (5), 581-95 (2021).

[19] Y. Li, F. Hu, Y. Liu, M. Ryan, R. Wang, A hybrid model compression approach via knowledge distillation for predicting energy consumption in additive manufacturing. International Journal of Production Research **24**, 1-23 (2023).

[20] P.V.R. Girish Kumar, K. Devaki Devi, Optimizing Mechanical Properties of Virgin and Recycled PLA Components Using Anova and Neural Networks. Mathematical Models in Engineering **10**, 1, 1-10 (2024).

DOI: https://doi.org/10.21595/mme.2023.23630