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Experimental Investigation of Process Parameters Affecting Mechanical Properties of FDM 3D Printed Polymers

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Abstract: This study investigates the mechanical properties of a polymer-based layered manufacturing (PLM) material fabricated using 3D printing technology. The research aims to evaluate the tensile, compressive, and flexural strength of the printed material under varying process parameters such as infill density, layer orientation, and printing speed. Standardized test specimens were printed using the Fused Deposition Modeling (FDM) technique and analyzed according to ASTM testing protocols. Tensile, compressive, and flexural tests were conducted using a Universal Testing Machine (UTM), and fracture surface analysis was performed through Scanning Electron Microscopy (SEM) to identify microstructural defects such as voids and interlayer adhesion issues. The results indicate that infill density and print orientation significantly influence the mechanical performance of the PLM material. Samples printed with 100% infill and 0° orientation exhibited the highest tensile and flexural strengths, while compression resistance increased with higher infill percentages. SEM analysis revealed that inadequate layer bonding and void formation contribute to material failure under stress. The findings emphasize the importance of optimizing printing parameters to enhance the structural integrity of 3D-printed materials. This study provides valuable insights for industries utilizing additive manufacturing in applications requiring mechanically robust polymer components. Future research may explore the reinforcement of PLM materials with composite additives and hybrid fabrication techniques to improve material properties. This study provides a comparative analysis of PLA, PETG, and ABS materials under identical printing conditions to identify optimal parameter combinations for enhanced mechanical performance.

1. INTRODUCTION

Polymer-based Layered Manufacturing (PLM) is a key aspect of 3D printing, allowing the production of customized and complex structures. Understanding the mechanical properties of PLM materials is essential for their application in industries such as aerospace, automotive, and biomedical engineering. This study evaluates the mechanical properties of a PLM material fabricated using 3D printing technology. The increasing demand for lightweight, strong, and durable materials has led to extensive research on the mechanical behaviour of these materials under different loading conditions.

1.1 Background

Additive Manufacturing (AM), commonly known as 3D printing, is a revolutionary technology that enables layer-by-layer construction of components from a digital model. Among various AM techniques, Fused Deposition Modelling (FDM) is widely used due to its cost-effectiveness and ease of operation. The mechanical properties of 3D-printed parts are influenced by several factors, including layer thickness, infill percentage, print orientation, and print speed. This study aims to evaluate how these parameters affect the strength and durability of PLM materials.

1.2 Importance of Mechanical Property Evaluation

Mechanical testing provides insights into the structural integrity of printed parts. Understanding the tensile, compressive, and flexural properties of PLM materials is critical for optimizing 3D printing parameters to achieve enhanced performance. The mechanical behavior of printed materials determines their suitability for industrial applications, such as load-bearing structures, biomedical implants, and automotive components.

1.3 Scope of the Study

This study focuses on the evaluation of mechanical properties of a specific PLM material manufactured using 3D printing. The study will:

• Investigate the tensile, compressive, and flexural strength of the printed material.

• Examine the effect of printing parameters on mechanical properties.
• Understand the impact of layer orientation and infill density.
• Compare experimental results with theoretical predictions.
• Analyse the microstructural characteristics using Scanning Electron Microscopy (SEM).

2.LITERATURE REVIEW

2.1 Overview of 3D Printing Technologies

3D printing technologies have evolved significantly over the past few decades. Some of the most common techniques include:
• Fused Deposition Modelling (FDM): Uses thermoplastic filaments that are extruded layer by layer.
• Selective Laser Sintering (SLS): Uses a laser to fuse powdered material.
• Stereolithography (SLA): Uses UV light to cure liquid resin.
• Direct Metal Laser Sintering (DMLS): Used for metal 3D printing.

2.2 Mechanical Behaviour of 3D-Printed PLM Materials

Numerous studies have investigated the mechanical properties of 3D-printed polymers. The mechanical strength of these materials depends on factors such as:
• Print Layer Thickness: Thicker layers may lead to weaker interlayer bonding, reducing overall strength.
• Infill Density: Higher infill percentages improve strength and durability.
• Print Orientation: Vertical and angled orientations affect stress distribution.
• Printing Temperature: Higher temperatures enhance layer adhesion.

Recent studies suggest that hybrid printing techniques, including reinforcement with carbon fibers and nanoparticles, can significantly enhance mechanical properties.

3. MATERIALS AND METHODOLOGY

3.1 Materials Used

The study uses a polymer-based material, commonly PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene) and PETG (Polyethylene terephthalate glycol) which is widely used in 3D printing. The filament properties include:
• PLA: High strength, biodegradable, and easy to print.
• PETG:balances strength and flexibility.
•ABS: Higher toughness, suitable for engineering applications.

3.2 Printer specification

The 3D printer used is based on the FDM (Fused Deposition Modeling) technique, with the following specifications:

•Nozzle Diameter**:** 0.4 mm

•Layer Height**:** 0.1 mm to 0.3 mm

•Printing Speed: 50-100 mm/s

•Extrusion Temperature**:** 200°C - 250°C

3.3 Specimen preparation

Standard test specimens are printed according to ASTM standards with varying infill densities (20%, 50%, 100%) and layer orientations (0°, 45°, 90°). Specimens include:

•Dog-bone specimens for tensile testing (ASTM D638)

•Cylindrical specimens for compression testing (ASTM D695)

•Rectangular bars for flexural testing (ASTM D790)

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3.4 Testing procedures

•Tensile Testing**:** Evaluated using a universal testing machine (UTM) to measure ultimate tensile strength and elongation.

•Compressive Testing: Conducted to determine material resistance under compressive loads.

•Flexural Testing: Used to assess bending strength and stiffness.

•Microscopic Analysis**:** SEM used for fracture surface analysis to detect defects like voids and delamination.

3.5. Method

In this study, each sample was printed with different combination of parameters with the main purpose of analyzing the influence of layer thickness, wall thickness, infill density, infill pattern parameters on the tensile strength and efficiency of printed parts. (shown in Table 1)

In the first step, it is necessary to build a 3D model with cad software (solidworks),as shown in figure 1.the printing is done with 3D printer. After the samples were printed , a tensile test was performed on each sample with Universal testing machine .

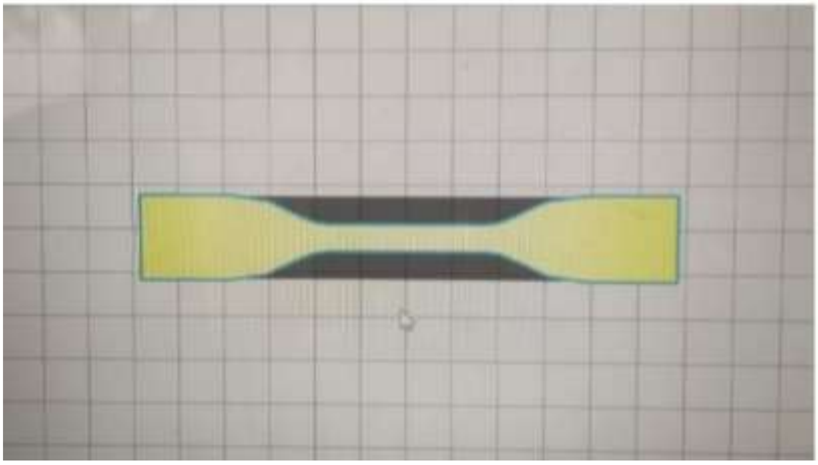

Figure 1. tensile test specimen

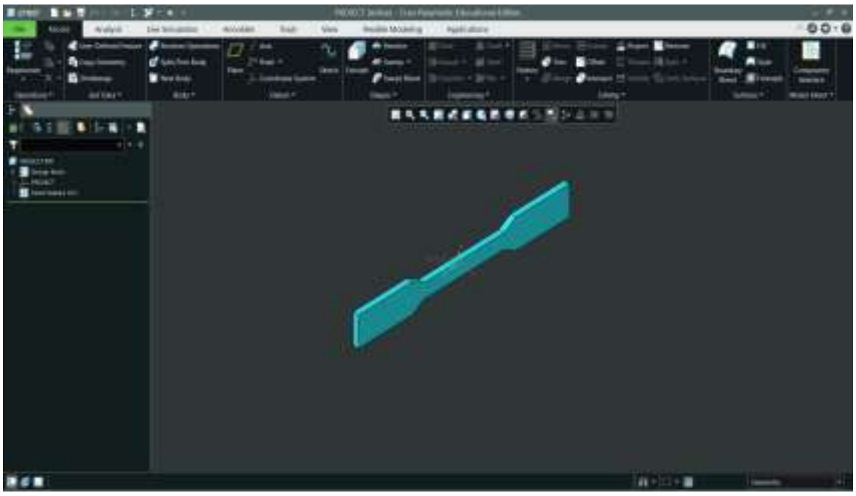

Figure 2. Solidworks software

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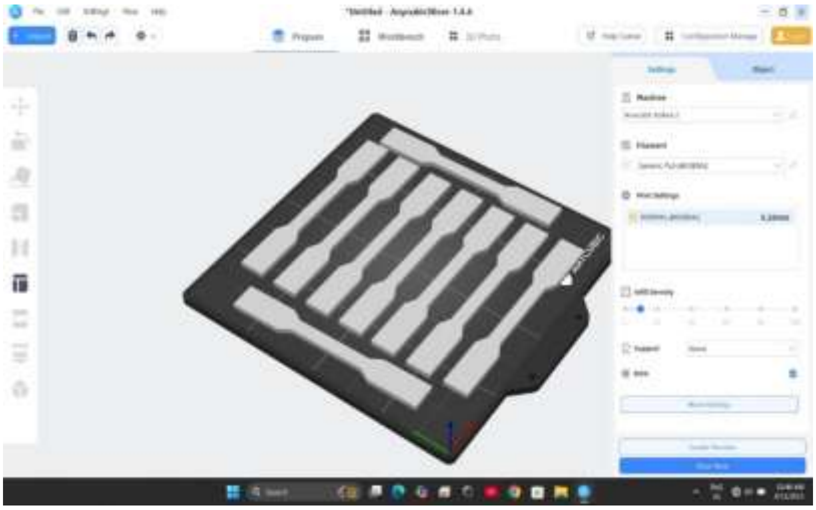

Figure 3. slicing software

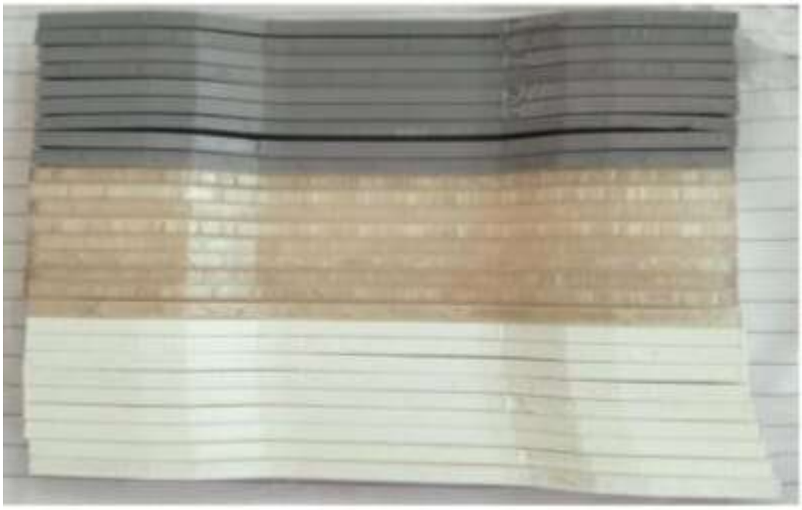

Figure 4. printed parts

Figure 5. Tensile test on universal testing machine

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Table 1. Printing parameters combination

Sr no	Material	Layer thickness	Infill pattern	% infill	Wall thickness
1	PLA	0.1	Cubic	10	0.4
2	PLA	0.2	Hexagonal	20	0.8
3	PLA	0.3	Tetragonal	30	1.2
4	PLA	0.2	Cubic	20	0.8
5	PLA	0.3	Hexagonal	30	1.2
6	PLA	0.1	Tetragonal	10	0.4
7	PLA	0.3	Cubic	30	1.2
8	PLA	0.1	Hexagonal	10	0.4
9	PLA	0.2	Tetragonal	20	0.8
10	PETG	0.1	Cubic	10	0.4
11	PETG	0.2	Hexagonal	20	0.8
12	PETG	0.3	Tetragonal	30	1.2
13	PETG	0.2	Cubic	20	0.8
14	PETG	0.3	Hexagonal	30	1.2
15	PETG	0.1	Tetragonal	10	0.4
16	PETG	0.3	Cubic	30	1.2
17	PETG	0.1	Hexagonal	10	0.4
18	PETG	0.2	Tetragonal	20	0.8
19	ABS	0.1	Cubic	10	0.4
20	ABS	0.2	Hexagonal	20	0.8
21	ABS	0.3	Tetragonal	30	1.2
22	ABS	0.2	Cubic	20	0.8
23	ABS	0.3	Hexagonal	30	1.2
24	ABS	0.1	Tetragonal	10	0.4
25	ABS	0.3	Cubic	30	1.2
26	ABS	0.1	Hexagonal	10	0.4
27	ABS	0.2	Tetragonal	20	0.8

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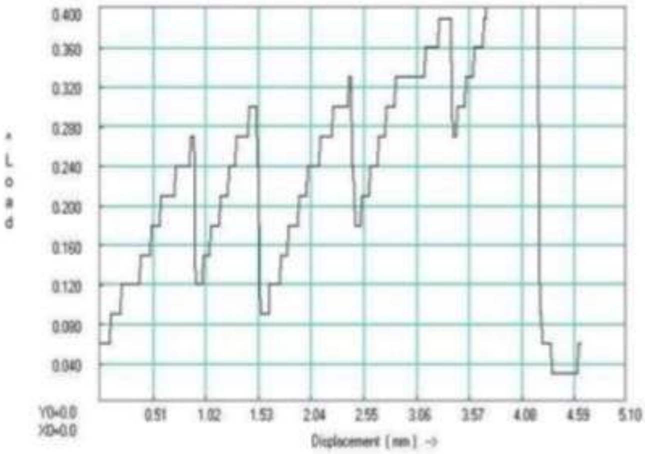
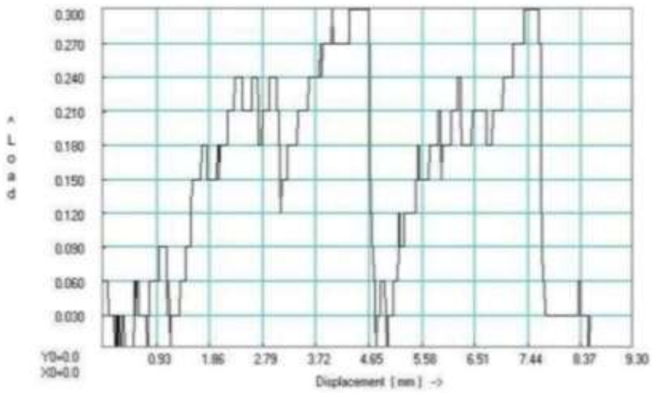
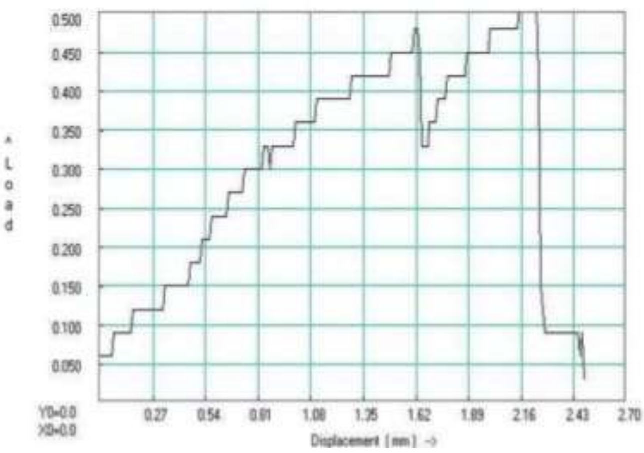


(a)



(b)



(c)

Figure 6.(a) Load Vs Displacement graph of ABS Material of specimen 1

(b) Load Vs Displacement graph of PETG Material of specimen 1

(C) Load Vs Displacement graph of PLA Material of specimen 1

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4. RESULTS AND DISCUSSION

Table 2. RESULTS OF UTS

Sr No	Max Force (kN)	Disp at Max Load	Max Disp (mm)	Tensile Strength (MPa)	Elongation
1	0.510	2.15	2.48	21.483	0.48
2	0.780	4	4.53	34.807	2.48
3	0.930	4.22	4.56	38.336	1.60
4	0.810	4.80	5.82	35.578	2.40
5	0.930	3.87	4.29	38.241	1.28
6	0.360	1.16	1.84	15.126	1.92
7	0.900	4.93	5.87	38.198	2.60
8	0.420	1.39	1.56	17.736	1.24
9	0.720	1.67	2.22	30.354	1.44
10	0.330	7.51	8.54	13.889	20.96
11	0.540	2.93	7.12	23.889	18.68
12	0.720	4.33	4.95	33.764	6.36
13	0.690	4.61	7.74	30.364	20
14	0.870	3.27	4.40	40.278	8.16
15	0.810	4.79	5.70	36.585	4.8
16	0.450	2.61	5.90	19.699	3
17	0.390	2.06	2.83	17.615	1.64
18	0.630	4.17	10.37	27.293	6.84
19	0.450	3.92	4.66	19.216	0.68
20	0.570	1.96	2.55	24.151	1.72
21	0.480	4.48	5.22	22.235	1.32
22	0.630	4.20	5.20	26.119	0.96
23	0.810	4.27	4.72	33.499	0.16
24	0.540	1.77	3.24	22.519	2.72
25	0.660	4.91	6.09	27.319	0.72
26	0.600	7.10	8.04	25	2.64
27	0.480	4.20	4.99	20.235	4.08

Maximum tensile strength observed ≈ 40 MPa (PETG/PLA cases)

Minimum ≈ 13 Mpa

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5.CONCLUSION

•In this project we have taken 5 parameters being material, wall thickness, layer height, infill density, infill pattern with 3 variables. By using taguchi method for optimization we have created 27 specimen parameters by using L27 array.

•The specimen number 7 (material-PLA, wall thickness-1.2mm, infill pattern- cubic, infill density- 30%, layer height-0.3 mm) exhibits highest ultimate tensile strength among 9 PLA material.

•The specimen number 14 (material-PETG, wall thickness-1.2 mm, infill pattern- hexagonal, infill density- 30%, layer height-0.3mm) exhibits highest ultimate tensile strength among 9 PETG material.

•The specimen number 1 (material-ABS, wall thickness-1.2 mm, infill pattern- cubic, infill density- 30%, layer height-0.3mm) exhibits highest ultimate tensile strength among 9 PETG material as well as among all 27 specimens.

•The valuable data collected during this project can also act as reference for further studies or rapid prototyping on Creality printer as it is evident from test conducted in the laboratory and the data gathered.

•Through 3D fused deposition modelling product printing single and multi-objective optimization case studies, this paper can conclude that the application of Taguchi design experiment matrix can help to reduce the number of experimentations as compared with other DoE methods and yields similar results.

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