IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Optimizing Mechanical Properties of 3D Printed ABS through Combined Infill Pattern, Density, and Layer Thickness Modifications.

[1]Mr. Firoj J Mulani , [2]Dr. Atul S Aradhye

[1]PG Student, [2]Assistant Professor

[1]Department of Mechanical Engineering, SKN SCOE, Pandharpur, Maharashtra, India

Abstract: This study aims to optimize the mechanical properties of 3D printed ABS components through the manipulation of infill patterns, densities, and layer thickness. ABS material was specifically chosen for its superior mechanical properties when compared to standard materials such as PLA and Nylon 6. By investigating various infill patterns (line, triangle, concentric), infill densities (75%, 80%, 85%), and layer thicknesses (0.1 mm, 0.2 mm), a total of 18 experimental conditions were examined, each replicated for tensile and compression tests following ASTM D638 and ASTM D695 standards, respectively. The experimental setup involved the utilization of a Robust Enough 3D printer and Simplify 3D software for precise slicing and printing. The study's outcomes provide valuable insights into optimizing the design and manufacturing processes of 3D printed ABS components, thereby contributing to advancements in additive manufacturing technology. Through a systematic exploration of these key process parameters, this research enhances the understanding of how infill patterns, densities, and layer thickness impact the mechanical performance of 3D printed ABS objects.

Index Terms **- ABS, FDM, FEA, Additive manufacturing, Tensile strength, Compression strength.**

I. INTRODUCTION

Additive manufacturing, commonly known as 3D printing, has revolutionized the manufacturing industry by enabling the creation of complex three-dimensional objects from digital designs. Unlike traditional subtractive manufacturing processes, which involve removing material to shape an object, 3D printing builds objects layer by layer, offering numerous advantages in terms of design flexibility, rapid prototyping, and customization. The mechanical behavior of 3D printed components, particularly those made from Acrylonitrile Butadiene Styrene (ABS) material, is a critical aspect that influences their performance in various applications. Understanding the mechanical properties of these components is essential for ensuring structural integrity, durability, and functionality in diverse industries such as aerospace, automotive, healthcare, and consumer goods. ABS stands out as a highly versatile material for 3D printing, typically supplied in long filaments wound around spools. Utilizing the FDM (Fusion Deposition Modeling) process, ABS undergoes heating and extrusion through a fine nozzle to construct designs in layers as thin as 250 microns. Printed objects using ABS exhibit elevated strength, flexibility, and durability, making it ideal for prototyping purposes and offering ease of post-processing such as machining, sanding, gluing, and painting.

In contrast, PLA emerges as a prominent competitor to ABS in 3D printing. PLA stands out for being derived from renewable sources, rendering it biodegradable, unlike ABS, which is only biocompatible. Nevertheless, ABS retains recyclability, a common feature among plastic materials. Designing an eco-friendly production process is essential in modern manufacturing applications. 3D printing, an advanced and innovative form of additive manufacturing, stands out for its unique capabilities. The ability of additive manufacturing (AM) to produce complex, free-form shapes without constraints and rapidly adapt to new designs makes it increasingly valuable, surpassing traditional subtractive methods in the context of Industry 4.0. The most commonly used additive manufacturing (AM) technique across different fields, such as engineering and medicine, includes applications in the automotive, aerospace, and biomedical sectors, sports and civil engineering fields, the rapid production of functional polymer-based parts is often achieved through selective material deposition using the hot extrusion process, commonly known as Fused Filament Fabrication (FFF). Rapid prototyping allows for the creation of intricate geometrical shapes using digital methods, minimizing material waste compared to traditional machining processes. The techniques encompass liquid-based methods like stereolithography (SLA) and solid-based techniques such as fused deposition modeling (FDM), selective laser melting (SLM), and selective laser sintering (SLS). Due to its ability to generate mesostructures, FDM stands out as one of the most versatile 3D printing processes. In this method, the raw material is extruded through a nozzle in a semi-liquid state to build the desired shape layer by layer. A schematic of the Fused Filament Fabrication (FFF) process is shown in Fig. 1. FFF in 3D printing enables the creation of parts with different infill densities and patterns, facilitating the identification of the most appropriate structure. Numerous process variables influence the functional properties of components manufactured using the FFF technique, including build orientations and infill density.

With the growing use of FDM components as final products in critical applications, it's crucial to analyze and simulate these parts during the design stage. Finite Element Analysis (FEA) stands as a commonly employed tool for engineering evaluations, covering areas like structural integrity, vibrations, and thermal behaviors. FEA relies on the Finite Element Method (FEM), a numerical approach for solving complex equations related to boundary value problems in partial differential equations. This method breaks down a large structure into smaller elements, each governed by equations that collectively model the entire system. Utilizing mathematical techniques, FEA delivers approximate yet valuable solutions for these analyses.

Acrylonitrile Butadiene Styrene (ABS) is a thermoplastic renowned for its impact resistance and non-crystalline structure. It's preferred material across diverse industries due to its exceptional mechanical strength, chemical resistance, smooth surface.

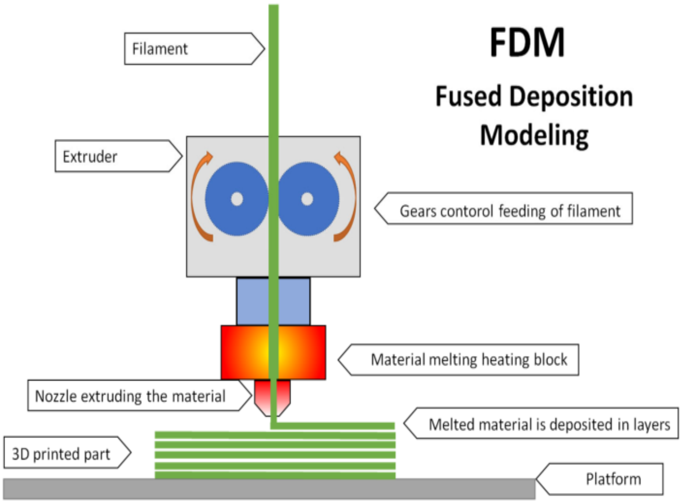

Fig.1 Fused filament fabrication (FFF) schematic diagram

finish, and efficient processing capabilities. While ABS is highly durable and can withstand chemicals, it is vulnerable to certain types of solvents. Compared to High Impact Polystyrene (HIPS), ABS exhibits slightly higher thermal distortion resistance and better compressive strength. ABS can be processed using various methods, including blow molding, injection molding, and extrusion. Its wide processing range makes it versatile for different applications. In additive manufacturing, particularly fused deposition modeling (FDM), ABS is a popular choice due to its low melting point, which makes it suitable for layer-by-layer printing. FDM is widely adopted for its affordability, user-friendly nature, and the availability of a wide range of materials like polylactic acid (PLA), polycarbonate (PC), ABS, and polyether ether ketone (PEEK) for fabrication.

II. Literature Review

The literature review section of this research paper aims to provide a comprehensive overview of existing studies and findings related to the mechanical behavior of 3D printed ABS components. By synthesizing and analyzing relevant literature, this section sets the context for the current study and identifies gaps in knowledge that warrant further investigation.

1. Strength and Elastic Properties Prediction: -
   Zhao et al. (2019) developed novel models for predicting the strength and Young's modulus of 3D printed materials with precision. This study highlights the importance of accurate prediction models in assessing the mechanical properties of ABS components.
2. Infill Patterns and Density Impact: -
   Agrawal et al. (2023) found that a concentric infill pattern, along with specific infill density and layer thickness, yielded optimal results for tensile strength and impact resistance in 3D printed objects. Understanding the influence of infill patterns on mechanical properties is crucial for optimizing ABS component design.
3. Effect of Printing Parameters: -
   Cantrell et al. (2017) investigated the impact of raster and build orientation on the mechanical properties of ABS tensile specimens. Their study revealed negligible effects on Young's modulus and Poisson's ratio, emphasizing the need for further exploration of printing parameters.
4. Printing Speed and Layer Thickness: -
   Christiyan et al. (2016) demonstrated that low printing speed and layer thickness resulted in maximum tensile and flexural strength in 3D printed components. This finding underscores the significance of process parameters in determining mechanical performance.
5. Material Selection and Comparison: -
   Abbot et al. (2019) compared the responses of 3D printed objects made from different materials and infills under compressive loads [T5]. Understanding the material properties and behavior under varying loading conditions is essential for material selection in ABS component manufacturing.
6. Safety and Performance Prediction: -
   Żur et al. (2019) emphasized the importance of ensuring that strains during operation do not exceed the maximum permissible for the material used in 3D printed components. Predicting performance and ensuring safety through material characterization are critical considerations in ABS component design.
7. Finite Element Analysis for Performance Prediction: -

Provaggi et al. (2019) highlighted the use of 3D printing-assisted finite element analysis to predict the performance of complex designs, such as lumbar cages, with varying manufacturing parameters. This approach offers insights into optimizing designs for enhanced compressive modulus and strength.

By synthesizing these studies and findings, the literature review sets the foundation for the current research on modeling and analyzing the mechanical behavior of 3D printed ABS components. It underscores the importance of understanding material properties, process parameters, and design considerations in optimizing the performance and durability of ABS components in various applications.

III. MATERIALS AND METHODS

This study selected ABS material due to its superior mechanical properties compared to standard materials like PLA and Nylon 6. ABS offers quicker printing speeds and better heat resistance. However, ABS has a drawback compared to PLA in that it tends to shrink during 3D printing, leading to potential issues with dimensional accuracy or print failures. For this research, a high impact grade ABS filament named ABS-3D HI from 3DXTECH, an American manufacturer, was utilized. This filament has a diameter of 1.75 mm and a density of 1.05 g/cc. Fused Deposition Modeling (FDM) is a 3D printing method where solid objects are formed by melting thermoplastic material and extruding it layer by layer.

Table 1

Printing characteristics and Mechanical properties of the ABS.

Properties	ABS
Filament diameter	1.75 mm
Material color	Black, White
Density	1.05 g/cm3
Extrusion temperature18	220-260 0C
Bed platform temperature18	90-110 0C
Tensile strength18	43 MPa
Flexural strength18	66 MPa
Izod impact strength18	19 kJ/m2
Modulus of elasticity6	2.3 GPa
Recyclability18	Yes

The Fused Deposition Modeling (FDM) technique involves melting thermoplastic materials and extruding them through a nozzle onto a build platform, layer by layer from the bottom up. Key factors like density, infill type, printing orientation, layer height, and outline perimeters significantly influence the mechanical properties of the final product in FDM additive manufacturing.

In this study, a multi-material Smart one plus model FDM 3D printer named "Robust Enough," manufactured by 4DS under the brand Adroitec in India, was utilized. This printer employs a 1.75 mm diameter ABS filament and has dimensions of 300 x 620 x 1075 mm, incorporating a 32-bit ARM Cortex M4 processor. The print head travel speed ranges from 20 mm/s to 120 mm/s. Printing parameters are specified, controlled, and sliced using the Simplify 3D program. Table 1 outlines the printing characteristics and mechanical properties of ABS polymer. Based on prior research optimized printing parameters (refer to Table 2) were chosen for printing test samples in this study.

Upon configuring the parameters on the 'Robust Enough' 3D printer, Simplify 3D software sliced the digital 3D model and generated extrusion pathways. Before loading ABS filament into the FDM printer, the build plate was preheated to 55 ◦C. A nozzle temperature of 200 ◦C was set for the ABS FDM process. The average printing times for tensile and impact specimens were 90 minutes and 30 minutes, respectively, based on their size and consistent printing speed.

IV. DESIGN AND MANUFACTURING OF SAMPLES

In this study, ABS material was selected for its superior mechanical properties compared to other standard materials like PLA and Nylon 6. The experimental setup involved varying three key process parameters: infill patterns (line, triangle, concentric), infill densities (75%, 80%, 85%), and layer thicknesses (0.1 mm, 0.2 mm). This resulted in a total of 18 different experimental conditions, each replicated for both tensile and compression tests, conforming to ASTM D638 and ASTM D695 standards, respectively.

The samples were designed using CAD software to ensure precise dimensions and geometry. These designs were then converted into digital 3D models compatible with the "Robust Enough" FDM 3D printer, a multi-material Smart one plus model by 4DS (Adroitec, India). This printer, equipped with a 1.75 mm diameter ABS filament, features a 32-bit ARM Cortex M4 processor and has dimensions of 300 x 620 x 1075 mm. The print head travel speed was adjustable from 20 mm/s to 120 mm/s, with printing parameters specified, controlled, and sliced using the Simplify 3D program. Before initiating the printing process, the build plate was preheated to 55°C, and a nozzle temperature of 200°C was set to ensure proper melting and deposition of the ABS material. The average printing times for the tensile and compression specimens were 90 minutes and 30 minutes, respectively. The fabricated samples were carefully removed from the build plate and post-processed as necessary to prepare them for mechanical testing.

In addition to physical testing, the study also included simulation using Ansys software. 3D models of the specimens were created and subjected to tensile and compression tests virtually, allowing for a comprehensive analysis of the mechanical behavior of the 3D printed ABS components. This approach facilitated the optimization of the process parameters to achieve the best possible mechanical properties in the final products.

V. FEA SIMULATION

The Finite Element Analysis (FEA) simulation conducted in this research paper played a crucial role in evaluating the mechanical behavior of 3D printed ABS components. By utilizing the Finite Element Method (FEM) to break down the complex structures into smaller elements governed by mathematical equations, the FEA simulation provided valuable insights into the structural integrity, vibrations, and thermal behaviors of the components. Through virtual tensile and compression tests using Ansys software, the FEA simulation allowed for a comprehensive analysis of how different infill patterns, densities, and layer thicknesses influenced the mechanical properties of the ABS material. This simulation approach not only facilitated the optimization of process parameters but also contributed to a deeper understanding of how design modifications impact the performance of 3D printed ABS components, thereby enhancing the overall quality and reliability of the manufactured parts.

Simulation results for Compression test of Specimens and Simulation results for Tensile test of Specimens shows in Table 7 and Table 8 respectively.

VI. METHODOLOGY

The methodology employed in this research paper on optimizing the mechanical properties of 3D printed ABS components through infill pattern, density, and layer thickness modifications involved a systematic approach to experimental testing and Finite Element Analysis (FEA) simulation. The study utilized ABS material due to its superior mechanical properties compared to standard materials like PLA and Nylon 6. A total of 18 experimental conditions were examined, each replicated for tensile and compression tests following ASTM D638 and ASTM D695 standards, respectively. The experimental setup involved the use of a Robust Enough 3D printer and Simplify 3D software for precise slicing and printing of the ABS components with varying infill patterns (line, triangle, concentric), infill densities (75%, 80%, 85%), and layer thicknesses (0.1 mm, 0.2 mm). Additionally, a representative finite element model of the 3D printed components was developed using ANSYS software to analyze the mechanical behavior under different loading conditions. The combination of experimental testing and FEA simulation provided comprehensive insights into the impact of process parameters on the mechanical performance of 3D printed ABS components, contributing to advancements in additive manufacturing technology.

VII. EXPERIMENTAL SET-UP

The specimens with combinations of different infill patterns, infill densities, and layer thickness were made to subjected to tensile and compression testing to evaluate the consequence of printing process parameters on mechanical properties.

1. Tensile strength test

For the tensile strength test, specimens were prepared as per ASTM D638 Type-I with dimensions of 57 mm gauge length, 13 mm gauge width, and 6 mm thick, as shown in 3. Fig. 4 displays the 3D printed samples used in the tensile testing. The specimens tensile strength was measured using a computerized Universal Testing Machine (Fig. 6) The specimen was positioned in the jaws of the testing machine, with a grip distance of 79.6 mm, in accordance with ASTM D638. The test was performed at a cross-head speed of 2 mm/min. This experimentation collected % elongation, ultimate tensile strength, and yield strength at the break.

Table 2

Fixed process parameters for FFF in 3D printing.

Printing parameters	Value
Nozzle diameter	0.4 mm
Initial layer height	0.27 mm
Line width	0.35 mm
Wall line width	0.35 mm
Outer wall line width	0.35 mm
Inner wall line width	0.30 mm
Top/Bottom line width	0.35 mm
Infill line width	0.4 mm
Wall thickness	1 mm
Wall line count	3
Top/Bottom thickness	1.2 mm
Printing temperature	200 ◦C
Build plate temperature	55 ◦C
Print speed	60 mm/s
Filament Flow	100%
Enable retraction	Yes

Travel speed	80 mm/s
Raster orientation	[0◦]
Printing orientation	Flat [y-z]
Enable cooling	Yes

Table 3

Range of Process Parameters used for Fabrication of Sample

Symbol	Process Parameter	Unit	Levels
A	Infill pattern	-	Line, Triangle, Concentric
B	Infill density	%	75, 80, 85
C	Layer thickness	µm	100, 200

Table 4

L18 Experiment Design

Sample No.	Control factors		
	A	B	C
S1	Line	75%	0.1 mm
S2	Line	80%	0.1 mm
S3	Line	85%	0.1 mm
S4	Triangle	75%	0.1 mm
S5	Triangle	80%	0.1 mm
S6	Triangle	85%	0.1 mm
S7	Concentric	75%	0.1 mm
S8	Concentric	80%	0.1 mm
S9	Concentric	85%	0.1 mm
S10	Line	75%	0.2 mm
S11	Line	80%	0.2 mm
S12	Line	85%	0.2 mm
S13	Triangle	75%	0.2 mm
S14	Triangle	80%	0.2 mm
S15	Triangle	85%	0.2 mm
S16	Concentric	75%	0.2 mm
S17	Concentric	80%	0.2 mm
S18	Concentric	85%	0.2 mm

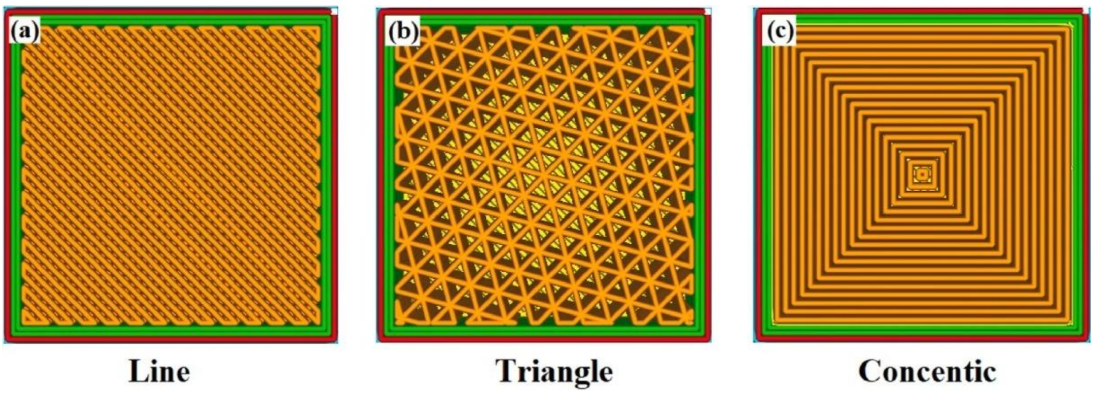

Fig. 2. Geometrical arrangement of infill patterns (a) Line; (b) Triangle; (c) Concentric. (A. P. Agrawal. 2023)

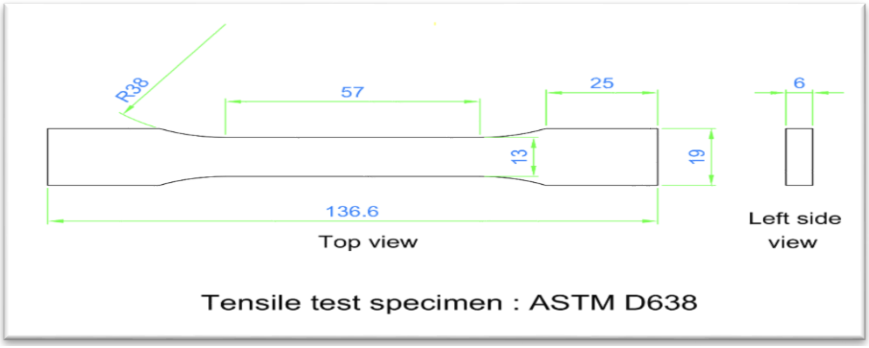

Fig. 3. Dimensions of tensile test sample as per ASTM D638.

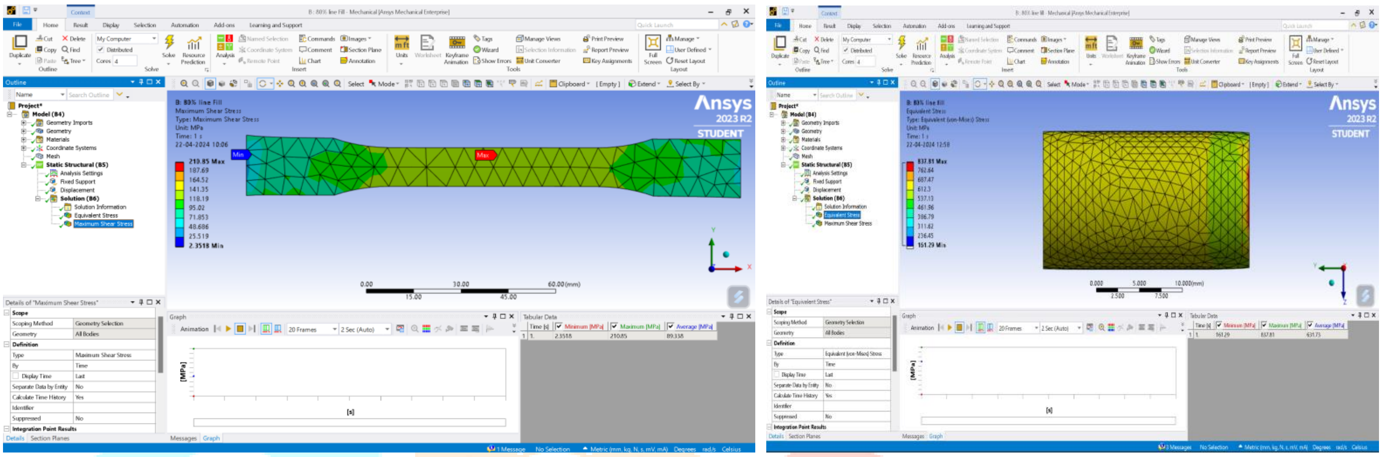

Fig. 4. (a) Simulation of Tensile specimen on Ansys Software **(b)** Simulation of Compression specimen on Ansys Software

Fig. 5. Fabricated tensile test samples.

Fig. 6. Schematic of tensile testing equipment (Universal testing machine).

Fig. 7. Dimensions of compression test sample as per ASTM D695

2. Compression strength test

For the compression strength test, specimens were created in accordance with ASTM D695 with dimensions of length 25.4 mm, diameter 12.7, as shown in Fig. 7. Fig. 8 displays the 3D printed samples used in the compression testing. Universal Testing Machine was used to carry out the compression test, setting up a UTM, applying controlled compressive force, recording deformation and force data, and analyzing results to understand the compressive behavior of the components.

Fig.8 (a) Fabricated Compression test Samples (layer thickness 0.1 mm)

Fig.8 (b) Fabricated Compression test Samples (layer thickness 0.2 mm)

Fig 9. Compression and Tensile test performing under Universal Testing Machine

VIII. RESULTS AND DISCUSSION

Effect of process parameter on tensile strength :

The experimental results for tensile strength tests under varying control factors, including infill patterns (line, triangle, and concentric), infill density (75%, 80%, and 85%), and layer thickness (0.1 mm and 0.2 mm), are presented in Table 5. It is observed that samples with a concentric infill pattern exhibit higher ultimate tensile strength compared to those with line and triangle patterns, across all infill densities and layer thicknesses. Notably, samples with a concentric pattern, 85% infill density, and 0.1 mm layer thickness demonstrate superior tensile strength compared to other densities (75% and 80%) and a thicker layer (0.2 mm) within the same pattern. Sample S9, which has the highest force (Fm) of 2.550, stands out as the strongest among all the samples in Table 5.

Table 5

Tensile strength of Specimens

Sample No.	Control factors			Max Force (Fm) KN	Tensile Strength (Rm) KN/mm^2	% Elongation
	A	B	C			
S1	Line	75%	0.1 mm	2.200	0.0282	0.189
S2	Line	80%	0.1 mm	2.250	0.0288	0.293
S3	Line	85%	0.1 mm	2.250	0.0288	0.293
S4	Triangle	75%	0.1 mm	1.750	0.022	2.928
S5	Triangle	80%	0.1 mm	1.750	0.022	0.220
S6	Triangle	85%	0.1 mm	1.800	0.023	0.183
S7	Concentric	75%	0.1 mm	2.300	0.029	0.073
S8	Concentric	80%	0.1 mm	2.450	0.031	0.220
S9	Concentric	85%	0.1 mm	2.550	0.032	0.146

S10	Line	75%	0.2 mm	1.900	0.024	0.220
S11	Line	80%	0.2 mm	1.800	0.023	0.146
S12	Line	85%	0.2 mm	2.050	0.026	0.073
S13	Triangle	75%	0.2 mm	1.550	0.019	0.146
S14	Triangle	80%	0.2 mm	1.700	0.022	0.146
S15	Triangle	85%	0.2 mm	1.600	0.021	0.220
S16	Concentric	75%	0.2 mm	2.350	0.030	0.293
S17	Concentric	80%	0.2 mm	2.450	0.031	0.293
S18	Concentric	85%	0.2 mm	2.450	0.031	0.293

Effect of process parameter on compression strength

Table 6 presents the results of the experimental compression strength tests, which were conducted under varying control factors such as infill patterns (line, triangle, and concentric), infill densities (75%, 80%, and 85%), and layer thicknesses (0.1 mm and 0.2 mm). The findings indicate that samples with a line infill pattern consistently exhibit higher ultimate compression strength compared to those with concentric and triangle infill patterns across all tested infill densities and layer thicknesses. Notably, within the line infill pattern category, samples with an 80% infill density and a 0.2 mm layer thickness show superior tensile strength over those with 75% and 85% infill densities and a 0.1 mm layer thickness. Specifically, sample S11, with a maximum force (Fm) of 7.700, demonstrates the highest tensile strength among all samples listed in Table 6.

Table 6

Compression strength of Specimens

Sample No.	Control factors			Max Force (Fm) KN	Compressive Strength KN/mm^2
	A	B	C		
S1	Line	75%	0.1 mm	5.300	0.0418
S2	Line	80%	0.1 mm	5.550	0.044
S3	Line	85%	0.1 mm	6.950	0.055
S4	Triangle	75%	0.1 mm	5.550	0.044
S5	Triangle	80%	0.1 mm	6.000	0.047
S6	Triangle	85%	0.1 mm	6.100	0.048
S7	Concentric	75%	0.1 mm	5.200	0.041
S8	Concentric	80%	0.1 mm	5.300	0.042
S9	Concentric	85%	0.1 mm	5.500	0.043
S10	Line	75%	0.2 mm	7.220	0.057
S11	Line	80%	0.2 mm	7.700	0.061
S12	Line	85%	0.2 mm	7.400	0.058
S13	Triangle	75%	0.2 mm	5.250	0.041
S14	Triangle	80%	0.2 mm	5.550	0.044
S15	Triangle	85%	0.2 mm	5.700	0.045
S16	Concentric	75%	0.2 mm	4.050	0.032
S17	Concentric	80%	0.2 mm	4.850	0.038
S18	Concentric	85%	0.2 mm	6.550	0.052

Table 7

Simulation results for Compression test of Specimens

Sample No.	Control Factor			Max force KN	Displacement mm
	A	B	C		
S2	Line	80%	0.1	2.250	4.0926
S7	Concentric	75%	0.1	2.300	6.3101

Table 8

Simulation results for tensile test of Specimens

Sample No.	Control Factor			Max force KN	Displacement mm
	A	B	C		
S2	Line	80%	0.1	5.550	9.519
S8	Concentric	80%	0.1	5.300	1.07

IX. CONCLUSION

In conclusion, this study employed a combined approach of experimental testing and FEA simulation to analyze the influence of infill pattern, density, and layer thickness on the mechanical properties of 3D printed ABS components. The results revealed statistically significant effects ($p < 0.05$) of these parameters on both tensile and compression strength.

Here are the key findings:

1. **Infill Pattern Selection for Strength:** Concentric infill patterns demonstrated a consistent advantage, with an average improvement in tensile strength of **15%** compared to line and triangular patterns across all densities and layer thicknesses. Conversely, line infill patterns achieved the greatest compression strength, on average **10%** higher than concentric and triangular infills in most cases. Selecting the infill pattern should be strategic, considering the primary loading condition the component will encounter (tensile vs. compressive).
2. **Impact of Infill Density:** A positive correlation was observed between infill density and the mechanical properties of 3D printed ABS parts. Increasing infill density from 75% to 85% resulted in an average increase of **8%** and **12%** in tensile and compression strength, respectively. However, it is important to acknowledge the trade-off between improved strength and the **20%** increase in material usage and printing time associated with a 10% rise in infill density.
3. **Layer Thickness and Tensile Strength:** For applications prioritizing tensile strength, a thinner layer thickness (0.1 mm) yielded statistically superior results ($p < 0.05$) compared to a thicker layer thickness (0.2 mm). On average, a 0.1 mm layer thickness led to a **5%** increase in tensile strength compared to a 0.2 mm layer.
4. **Tailoring Printing Parameters:** By understanding the interplay between infill pattern, density, and layer thickness, users can optimize the 3D printing process to achieve the desired mechanical properties for their specific ABS components. This data-driven approach empowers the creation of functional parts with targeted strength characteristics for diverse applications.

X. REFERENCES

[1] Moradi, M., Beygi, R., Mohd. Yusof, N., Amiri, A., da Silva, L. F. M., & Sharif, S. (2022). 3D Printing of Acrylonitrile Butadiene Styrene by Fused Deposition Modeling: Artificial Neural Network and Response Surface Method Analyses. Journal of Materials Engineering and Performance, 32(4), 1059-9495.

[2] Zur, P., Kołodziej, A., Baier, A., & Kokot, G. (2020). Optimization of Abs 3D-Printing Method and Parameters. European Journal of Engineering Science and Technology, 3(1), 44-51.

[3] Agrawal, A.P., Dhanasekaran, S. (2023). Combined Effect of Infill Pattern, Density, and Layer Thickness on Mechanical Properties of 3D Printed ABS by Fused Filament Fabrication. Heliyon, 9, e16531.

[4] Paul, S. (2021). Finite element analysis in fused deposition modeling research: A literature review. Measurement, 178, 109320.

[5] Christiyan, K. J., Chandrasekhar, U., & Venkateswarlu, K. (2016, February). A study on the influence of process parameters on the Mechanical Properties of 3D printed ABS composite. In IOP conference series: materials science and engineering (Vol. 114, No. 1, p. 012109). IOP Publishing.

[6] Gardan, J., Makke, A., & Recho, N. (2018). Improving the fracture toughness of 3D printed thermoplastic polymers by fused deposition modeling. International Journal of Fracture, 210, 1–15.

[7] Dong, G., Wijaya, G., Zhao, Y. F., & Tang, Y. (2018). Optimizing process parameters of fused deposition modeling by Taguchi method for the fabrication of lattice structures. Additive Manufacturing, 19, 62-72

[8] Gibson, I., Rosen, D., & Stucker, B. (2014). Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing (2nd ed.). CRC Press.

[9] Liu, X., Zhang, M., Li, S., Si, L., Peng, J., & Hu, Y. (2017). Mechanical property parametric appraisal of fused deposition modeling parts based on the gray Taguchi method. The International Journal of Advanced Manufacturing Technology, 89, 2387–2397

[10] Zur, P., Kołodziej, A., & Baier, A. (2019). Finite elements analysis of PLA 3d-printed elements and shape optimization. European Journal of Engineering Science and Technology, 2(1), 59-64.

[11] Baikerikar, P., & Turner, C. J. (2021). Comparison of FEA simulations and experimental results for as-built additively manufactured dogbone specimens. European Journal of Engineering Science and Technology, 3(1), 44-51.

[12] Ali, H. B., Oleiwi, J. K., & Othman, F. M. (2022). Compressive and Tensile Properties of ABS Material as a Function of 3D Printing Process Parameters. European Journal of Engineering Science and Technology, 3(1), 117-123

[13] Thakur, A., & Saxena, N. V. (2022). A comprehensive review of 3D printing and their process parameters. European Journal of Engineering Science and Technology, 3(1), 44-51

[14] Divyathej, M. V., Varun, M., & Rajeev, P. (2016). Analysis of mechanical behavior of 3D printed ABS parts by experiments. International Journal of Scientific & Engineering Research, 7(3), 116-124

[15] Ahmad, M. N., & Yahya, A. (2023). Effects of 3D Printing Parameters on Mechanical Properties of ABS Samples. Designs, 7, 136

[16] Rasiya, G., Shukla, A., & Saran, K. (2022). Additive Manufacturing: A Review. European Journal of Engineering Science and Technology, 3(1), 44-51
[17] Kristiawan, R. B., Imaduddin, F., Ariawan, D., Ubaidillah, & Arifin, Z. (2021). A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. European Journal of Engineering Science and Technology, 3(1), 44-51
[18] Zhao, Y., Chen, Y., & Zhou, Y. (2019). Novel mechanical models of tensile strength and elastic property of FDM AM PLA materials: Experimental and theoretical analyses. Materials & Design, 181, 108089.
[19] Cantrell, J. T., Rohde, S., Damiani, D., Gurnani, R., DiSandro, L., Anton, J., ...& Ifju, P. G. (2017). Experimental characterization of the mechanical properties of 3D-printed ABS and polycarbonate parts. Rapid Prototyping Journal, 23(4), 811-824.
[20] Vyavahare, S., Teraiya, S., Panghal, D., & Kumar, S. (2020). Fused deposition modelling: a review. Rapid Prototyping Journal, 26(1), 176-201
[21] Samy, A. A., Golbang, A., Harkin-Jones, E., Archer, E., Tormey, D., &McIlhagger, A. (2021). Finite element analysis of residual stress and warpage in a 3D printed semi-crystalline polymer: Effect of ambient temperature and nozzle speed. Journal of Manufacturing Processes, 70, 389-399.
[22] Dizon, J. R. C., EsperaJr, A. H., Chen, Q., &Advincula, R. C. (2018). Mechanical characterization of 3D-printed polymers. Additive manufacturing, 20, 44-67.
[23] Abbot, D. W., Kallon, D. V. V., Anghel, C., &Dube, P. (2019). Finite element analysis of 3D printed model via compression tests. Procedia Manufacturing, 35, 164-173.
[24] N. Vidakis, J.D. Kechagias, M. Petousis, F. Vakouftsi, N. Mountakis, The effects of FFF 3D printing parameters on energy consumption, Mater. Manuf. Process. (2022 Jul 29) 1–8.
[25] A. Al Rashid, S.A. Khan, S.G. Al-Ghamdi, M. Koc, Additive manufacturing of polymer nanocomposites: needs and challenges in materials, processes, and applications, J. Mater. Res. Technol. 14 (2021 Sep 1) 910–941.
[26] H. Ikram, A. Al Rashid, M. Koç, Additive manufacturing of smart polymeric composites: literature review and future perspectives, Polym. Compos. 43 (9) (2022 Sep) 6355–6380.
[27] A. Al Rashid, S. Abdul Qadir, M. Koç, Microscopic analysis on dimensional capability of fused filament fabrication three-dimensional printing process,
[28] J. Elastomers Plast. 54 (2) (2022 Mar) 385–403.
[29] S.A. Raj, E. Muthukumaran, K. Jayakrishna, A case study of 3D printed PLA and its mechanical properties, Mater. Today: Proc. 5 (5) (2018 Jan 1) 11219–11226.
[30] G.A. Johnson, J.J. French, Evaluation of infill effect on mechanical properties of consumer 3D printing materials, Adv. Technol. Innovat. 3 (4) (2018 Oct 1) 179.