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Impact of Layer Height and Infill Line Orientation On 3D Printed Components Produced Via Additive Manufacturing

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Abstract

Additive Manufacturing (AM) is an extrusion-based technique used to create objects by extruding semi-molten material through a nozzle of specific dimensions. Materials like acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), and others are commonly employed in this process to manufacture industrial components. The mechanical properties of engineering component are critical for various industrial applications. This study investigates the impact of additive manufacturing on fabrication, considering different process parameters. Standard specimens were fabricated for testing and analysis. The maximum experimentally determined tensile strength was 39.574 MPa, achieved at a layer height of 0.10 mm and an infill line orientation of 90^0. The influence of various process parameters on the tensile mechanical properties was statistically analyzed and optimized using a genetic algorithm (GA). The results show a significant improvement in optimised conditions. GA predicted a tensile strength of 40.045 MPa under optimized conditions, with a layer height of 0.102 mm and an infill line direction of 89^0. Experimental validation confirmed the GA's prediction, yielding a tensile strength of 41.50 MPa for the optimized parameters. This represents a 4.86% improvement over the initial maximum tensile strength, with a prediction error of 3.50%. The results demonstrate the feasibility and effectiveness of the study for the selected application.

Keywords: Additive manufacturing, tensile mechanical strength, genetic algorithm.

INTRODUCTION

Product manufacturing has intensified the high demand for quality products with higher flexibility and efficiency. Due to drawbacks with the conventional manufacturing process, Additive manufacturing (AM) technology is gaining immense popularity among industrial establishments for fabricating products with higher flexibility and speed without losing quality. In this technology, materials are joined layer by layer to make an object from a 3D CAD file. It is opposed to subtractive manufacturing processes as the advancement in direct technology produces low volume. AM has been fruitful in serving the rapidly required end products for defense, automobiles, healthcare, domestic appliances, etc [1-4]

Fused deposition modelling, often known as FDM, is an AM process based on extrusion and fabricating objects by forcing semi-molten material through a nozzle with a very particular aperture [5]. FDM technology has been widely accepted by the material extrusion process for various polymers, mainly because it is inexpensive and straightforward. This technique utilizes polylactic acid (PLA), polycarbonate (PC), acrylonitrile butadiene styrene (ABS), and other materials for

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producing industrial parts. The significant components of FDM technology contain filament spool, driving wheels, and liquefier; build platform, etc., as shown in Figure 1.

FDM technology has grown into one of the most promising component fabrication techniques. The mechanical properties and part qualities largely depend upon the selection of parameters used in the process. Each process parameter plays a different and significant role in deciding the material's property. Combining the various process parameters gives properties that are difficult to understand. Therefore, investigating parameters for desired properties essential from the application perspective, such as gears, hooks, hangers, etc. The research also indicates that processing factors impact the characteristics of FDM-fabricated objects. Even though much research has been devoted to determining the optimal parameter settings to enhance the quality and performance of final goods, it remains to be seen which parameters should be optimized.

Djokikj et al. [6] examined the tensile and flexural mechanical characteristics of several polymeric materials, including PLA, PC, and PETG, generated using the FDM technique with varied combinations of parameters. The author demonstrates that a smaller layer thickness and a higher printing temperature are advantageous for enhancing component qualities.

Nathaphan et al. 2021 [7] studied the interaction impact of processing factors on he compressive mechanical behavior and dimensional precision of ABS components. The authors also approached finding optimum processing conditions to attain the desired compressive strength with suitable parts dimensions with multiple input settings like build orientation, extruder temperature, bed temperature, layer height, the number of shells, and print head speed. In line with other studies, the results show that lower layer thickness and print head speed favour better compressive mechanical strength. They determined that build direction and layer height are the essential characteristics to be emphasized during parametric analysis. Additionally, the build platform should be kept overhead of the glass transition range of thermoplastic material.

Yang et al. [8] analyzed the FDM operation factors such as nozzle aperture, extrusion temperature, layer height, and extrusion & filling velocity to achieve optimum tensile mechanical strength with minimal surface roughness and component build time. The optimization has been performed through RSM and NSGA-II, and experiments validate the results. It is found that layer height and nozzle opening are the most influencing factors for selected responses. The temperature of the nozzle has no substantial impact on the surface quality of the pieces. The higher nozzle opening, filling velocity and layer height values positively influence the built time. The results suggested that the same parameters may affect the material weight and dimensional performance.

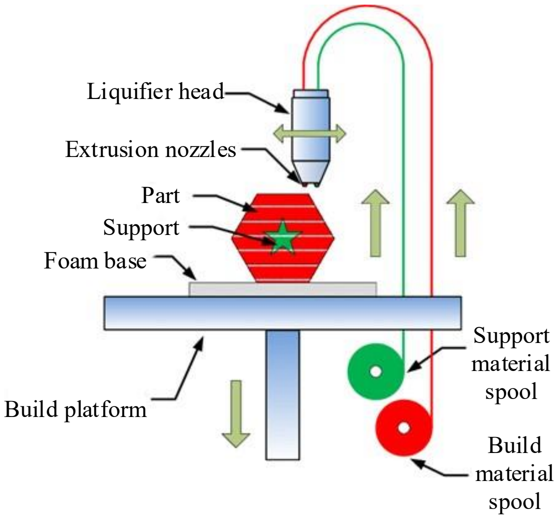

Figure 1. Components of FDM technology.

Mendricky et al. 2020 [9] analyzed the influence of FFF operation parameters on the quality and precision of polymeric components. Polylactic acid is utilized as the material of construction. The authors considered 13 process parameters to investigate their effect on manufacturing time, material weight, surface roughness and accuracy. The DoE Taguchi approach and Paret's rule are employed for experimental design and analysis. The material weight is significantly affected by % filling, number of walls and layer thickness. The layer thickness was also identified as a critical factor in determining the surface roughness of the components. Many authors have performed the optimization of process parameters through different approaches. For various applications, tests were conducted to evaluate the operating parameters, including layer height, raster orientation, and nozzle temperature.

The present work deals with optimizing the tensile strength of ABS parts. Firstly, tensile strength is calculated for various combinations of layer height (1.0, 0.15, 0.2) and raster angle (45°, 55°, -55°, 60°, 90°). After that, ANOVA and GA are applied to optimize process parameters to obtain maximum strength and validate results with experiments.

MATERIAL AND METHODS

ABS thermoplastic is considered the fabrication material in this investigation. The significant steps to fabricate the parts are indicated in Figure 2. First, the CAD model of the desired product is developed, which is converted to a format acceptable to the AM systems. Generally, the STL file format is used as an interface between the slicing software and AM systems. The STL file contains information about the shape, size, and other specifications of the part to be printed. As the extruded material is melted, the new layers are joined with the previous layer. This procedure is continued until the desired result is achieved [10– 17].

The specimens are fabricated corresponding to variables, layer height and raster orientations. The considered variable parameters are shown in Table 1 at various levels. The dimensions of samples are maintained in accordance with ASTM specifications. The tensile test specimens adhered to the ASTM D638 specification. Figure 3 (a) and (b) depict a tensile test specimen's dimensions and CAD model.

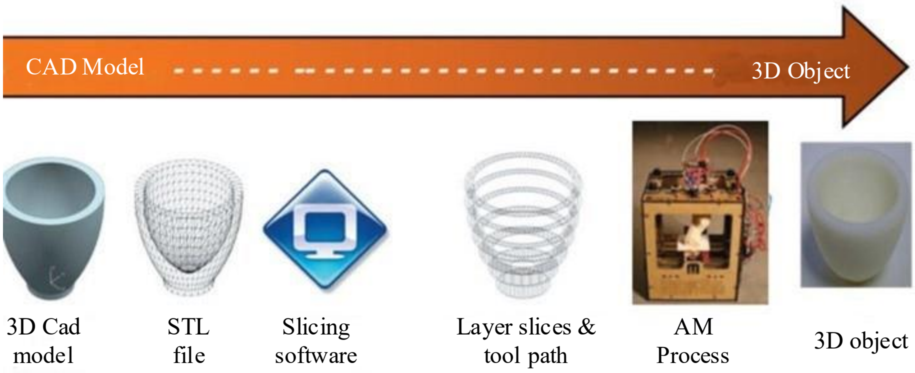

Figure 2. Steps used in part fabrication.

Table 1. Process parameters.

Category of parameters	Parameters	Values at different levels
Variable Parameters	Layer height (mm)	0.1, 0.15 and 0.2
	Raster orientation (Degree)	45°, 55°, -55°, 60° and 90°
Fixed parameters	Feed rate (mm/s)	40
	Infill Pattern	Grid
	Infill Density	40%
	Printing Temperature (°C)	230
	Platform Temperature (°C)	80

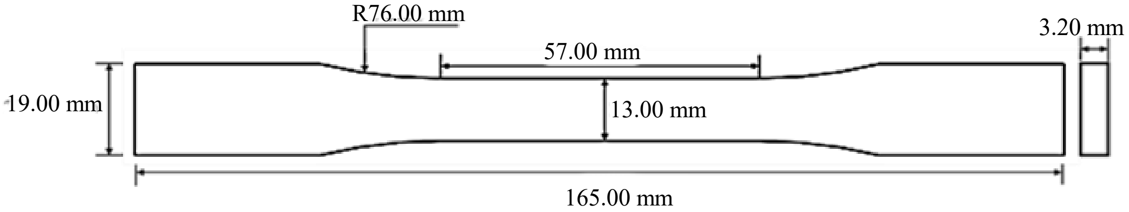

Figure 3. ASTM-D638 Tensile test specimen.

Figure 4. (a) Test setup (b) view of a fractured specimen.

As shown in Figure 4, the tensile mechanical strength test is performed on a universal testing machine (UTM) with a maximum pulling force of 100 kN. Figure 4 (a) and (b) show the test setup and a view of a fractured specimen during tensile testing in the lab.

The genetic algorithm (GA) is used for the optimization of parameters. This approach creates mathematical equations for tensile strength as regression equations. These regression equations are then considered fitness functions for GA. An example of a search heuristic is the genetic algorithm, which bases its operations on natural heredity [18], [19]. It suggests a process analogous to how nature chooses the individuals with the most successful offspring in the subsequent generation. GA represents the fitness function as an equation with predetermined constraints, and these constraints used for all models are $0.1 \leq A \geq 0.2$ and $-55 \leq C \geq 90$.

RESULTS AND DISCUSSION

Table 2 provides the findings from tensile tests conducted according to the specified specifications. Figure 5 indicates the tensile strength values, which enables us to compare analysis with the variation of process parameters. The maximum tensile peak stress, i.e., 39.574 MPa, is obtained for 0.1 mm layer height and 90° infill line direction.

Figures 7 depict the main effect and contour plots of tensile strength for the specimens. The main effect plot of the tensile test shows the lower layer height with 60° raster orientation providing better results. The contour plot shows that the tensile strength increases by increasing the infill line direction value with lower layer height.

Figure 6 contrasts the fractured morphology of tensile specimens with varying layer heights. The specimen manufactured with an LH of 0.1mm and a layer height of 0.2mm exhibits ductile failure with raster dragging and necking and brittle failure, respectively. The specimen displays a combination of ductile and brittle failure as the Layer height increases from 0.1mm to 0.15mm.

Table 2. The result was obtained after performing a tensile test.

S N.	Layer height	Infill line direction	Peak stress (MPa)
1	0.1	45	38.39
2	0.1	55	39.304
3	0.1	-55	38.211
4	0.1	60	38.884
5	0.1	90	39.574
6	0.15	45	34.318
7	0.15	55	34.895
8	0.15	-55	33.583
9	0.15	60	37.424
10	0.15	90	36.88
11	0.2	45	37.064
12	0.2	55	29.582
13	0.2	-55	34.964
14	0.2	60	37.146
15	0.2	90	36.994

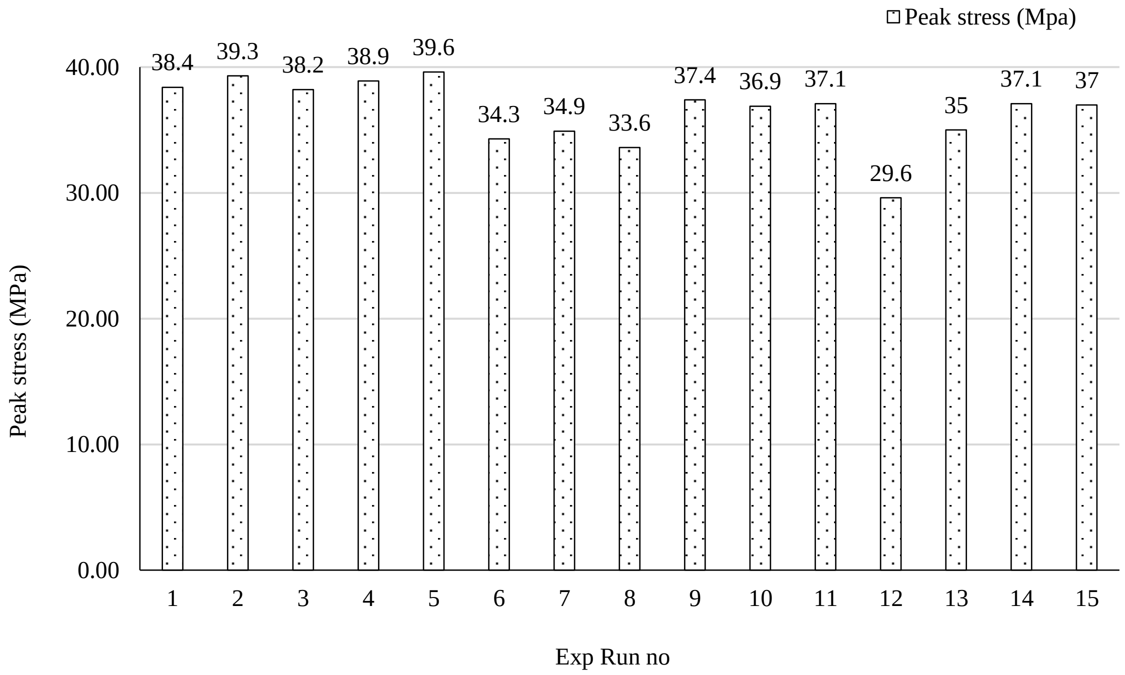

Figure 5. Tensile test results.

Because there were more layers with a lower layer height, additional bonding lines developed, reducing the likelihood of layer dislocation and increasing layer strength at a lower layer height.

Variations in layer height and infill orientation significantly impact the failure mechanisms of 3D-printed parts. Lower layer heights improve interlayer bonding, tensile strength, and surface finish, leading to ductile failure, while higher layer heights increase voids and defects, making the part prone to brittle failure and delamination. Infill aligned with the load direction enhances strength and durability, whereas perpendicular infill weakens the structure, increasing the risk of shear failure. A 45°/−45° infill offers balanced strength but exhibits mixed failure modes. Optimizing these parameters is crucial for enhancing structural integrity and performance in 3D-printed components.

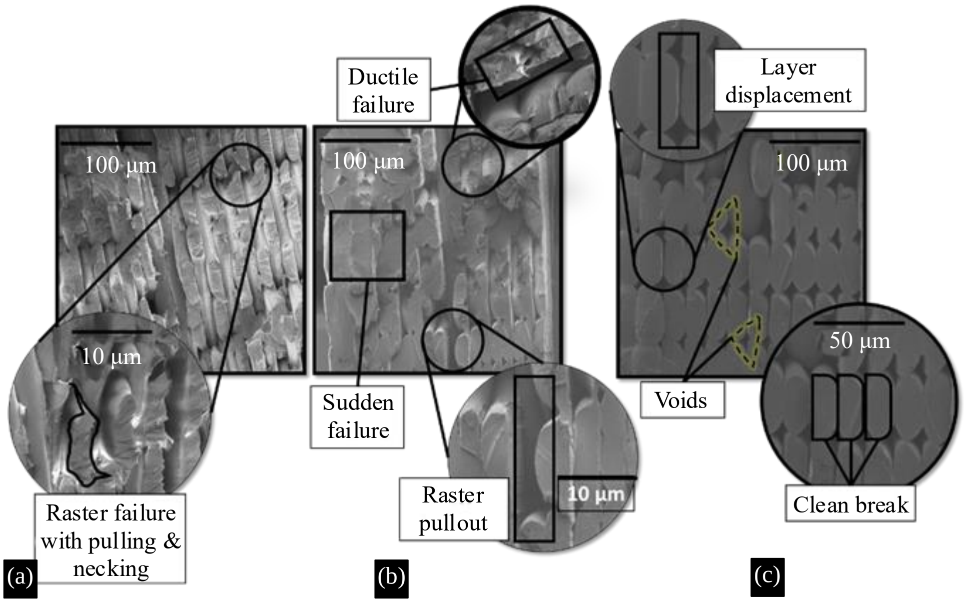

Figure 6. Comparison of the fractured morphology of specimens built at Layer height (a) 0.1mm (b) 0.15mm(c) 0.2mm

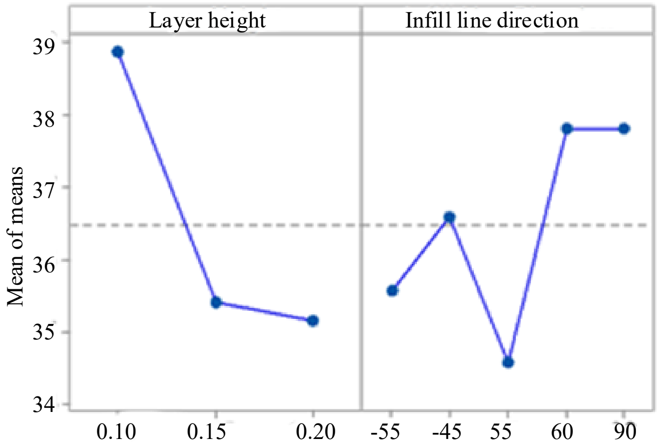

Figure 7. Main effect plot for tensile strength.

Based upon the analysis of experimental data, the regression model is obtained through Eq. 1. This model is now used to optimize the genetic algorithm as the fitness function. Using ANOVA, the determination coefficient value is used to assess the validity of this model. The bigger the determination coefficient's deal, the better the model's fit with the data. The ANOVA results are reported in Table 3, which suggests that the established model can accurately predict variations in strength. The p-value represents the level of significance for parameter combinations. With low p values, the relevance of process factors for maximizing the tensile strength of components increases. The effects of layer thickness are the most significant in this research, as demonstrated by p values less than the alpha value, i.e., 0.05. The computed value of p for the model is likewise less than alpha, i.e., 0.041, indicating that the model is statistically significant.

Equation 1 demonstrates the developed model using experimental analysis. The model is then taken as a fitness function for optimization using GA; Figure 8 exhibits the Pareto front obtained through a genetic algorithm. The graph showing the best and mean values of the fitness function corresponding to the optimum parameters setting is 40.04512 MPa and 40.04621 MPa, respectively.

$$\text{Peak Stress (MPa)} = 41.58 - 37.2\ \text{Layer Height} + 0.0124\ \text{Infill Line Direction} \quad (1)$$

Table 3. ANOVA.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	2	40.247	20.123	4.22	0.041
Layer Height	1	34.644	34.644	7.26	0.020
Infill Line Direction	1	5.602	5.602	1.17	0.300
Error	12	57.285	4.774		
Total	14	97.531			
SD	2.18488				

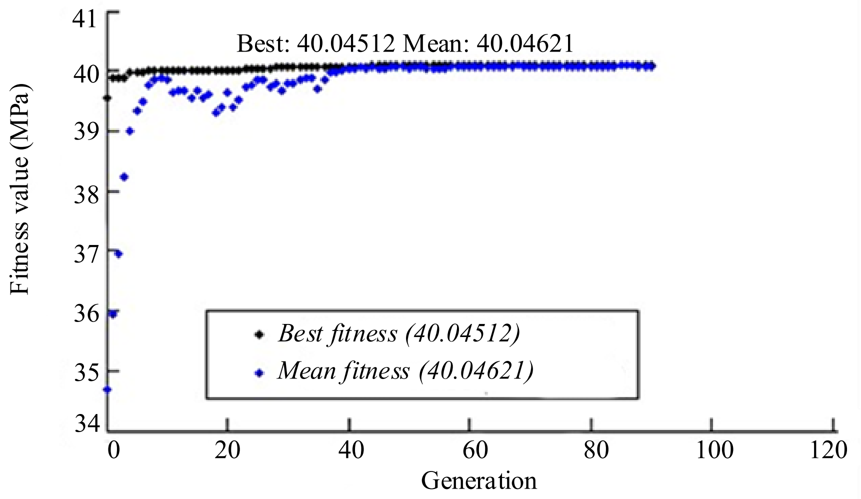

Figure 8. Pareto graph obtained through GA.

Table 4. Comparative comparison of testing outcomes using reference samples.

Parameters		**Tensile strength (MPa)**		**PPE (%)**
Layer height	***Infill line direction***	***GA predicted***	***Experimental***	
0.102	89°	40.04512	41.50	3.50

The optimized model through GA provided improved results. The optimum value of process parameters obtained by GA is layer height 0.102 mm and infill line direction 89°. The fitness value, i.e., tensile strength corresponding to the optimized parameters, improved by 1.190 %, compared to the highest value of all experiments. The same set of parameters fabricates the specimen to validate predicted results. At the determined model parameters, the experimental strength value is 41.50 MPa. At the same time, the predicted tensile strength is 40.04512 MPa. To validate the results of the GA technique, the percentage expected error is calculated using equation 2, which shows an avoidable error of 3.50 %, as shown in Table 4.

$$\mathrm{PPE} = \frac{\mathrm{E_i} - \mathrm{P_i}]}{\mathrm{E_i}} * 100 \qquad (2)$$

CONCLUSIONS

In conclusion, the study investigated the effect of additive manufacturing parameters, specifically layer height and infill line direction, on the tensile characteristics of thermoplastic materials. The results showed that optimizing these parameters using the genetic algorithm (GA) technique led to improved tensile strength.

The GA optimization predicted an optimal set of parameters with a layer height of 0.102 mm and an infill line direction of 89°, resulting in a predicted tensile strength of 40.04512 MPa. Experimental validation confirmed the effectiveness of the GA technique, as the achieved tensile strength for these parameters was 41.50 MPa, showing a 4.86% improvement over the initial maximum practical value.

This study highlights the significance of process parameters in additive manufacturing and the potential of optimization techniques like genetic algorithms (GA) to enhance material properties. By controlling these parameters, manufacturers can improve the tensile strength of thermoplastics, making them more suitable for engineering applications. Future research can focus on advanced materials, such as fiber-reinforced composites, and refining printing parameters to enhance durability. Post-processing methods like annealing, resin coating, and chemical treatments can further improve mechanical properties by strengthening interlayer bonding, reducing defects, and enhancing surface quality. Additionally, multi-axis printing and hybrid manufacturing can address anisotropic weaknesses, while AI-driven modeling can optimize designs. Exploring biodegradable and high-performance thermoplastics will expand FDM’s applications in aerospace, healthcare, and other industries.

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