International Journal of Computational Methods and Experimental Measurements
Vol. 13, No. 1, March, 2025, pp. 133-140
Journal homepage: http://iieta.org/journals/ijcmem

Characterizing and Optimizing the Parameters of Additive Manufacturing by Fused Deposition Modeling Methods to Enhance the Product Mechanical Qualities

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https://doi.org/10.18280/ijcmem.130114

Received: 20 October 2024
Revised: 7 February 2025
Accepted: 14 March 2025
Available online: 31 March 2025

Keywords:
acrylonitrile butadiene styrene (ABS), ANOVA, Fused Deposition Modelling (FDM), mechanical properties, Taguchi approach

ABSTRACT

This paper focuses on the study of the use of fused deposition modeling (FDM) in enhancing the process parameters of formed components. Three variables (fill density, layer height, and printing speed) are considered to have a significant and significant effect on the tensile strength of acrylonitrile butadiene styrene specimens. The methodology of this study is based on experiments using the Taguchi strategy. On the other hand, previous studies have mainly focused on analyzing individual process parameters and their effect on the mechanical properties of FDM-manufactured parts. The results of this study, using Taguchi techniques and analysis of variance, show that the largest and most significant effect on the tensile strength of FDM structures was the fill density among the three process parameters. ANOVA results for the average tensile strength with a confidence interval of 66.595%, while ANOVA results for the Young Modulus at a confidence interval of 36.236% and the ANOVA findings for the fractured strength at a confidence interval of 50.228%. A higher F-value indicates that adjusting a process parameter has a greater impact on performance characteristics. In addition, there is a limited effect of the other process variable with a smaller effect, but it was still effective. Finally, valuable insights could be drawn from the results about the correlation between process parameters and mechanical properties of components. The study confirms encouraging results using FDM technology for researchers and future studies in terms of enhancing the structural integrity of the produced components.

1. INTRODUCTION

To generate a hierarchical product directly from a computer-aided design (CAD) file, additive manufacturing (AM) is the first and primary choice to meet this. Additive manufacturing is a technology that has been widely used for hierarchical 3D design as an advanced technology in this field and is known as 3D Printing [1, 2]. CAD software is used to provide instructions and commands in the design of the dedicated layers in various geometric patterns, where CAD works in AM to benefit from it in 3D scanners [3, 4]. Recently, rapid growth has been observed in the development of AM as it has become part of various manufacturing processes for wide fields such as agriculture, healthcare, automobiles, etc., as AM is adaptable and effective in every field where it is needed [5, 6]. Therefore, it has been realized that there is an increasing need for its use on a wide scale, for example, its use in customized components and prosthetics [7]. AM encompasses a diverse array of methods, including the fabrication of three-dimensional objects by gradually adding material layer by layer. The different processes involved are vat photopolymerization, powder bed fusion, sheet lamination, binder jetting, directed energy deposition, extrusion, and jetting of material [1].

The FDM-compatible thermoplastic polymers and reinforced materials include fiber-reinforced thermoplastics, Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polyether Ether Ketone (PEEK), and polycarbonate [8, 9]. Recent years have seen an upward trend in research on the properties of materials created with FFF, particularly in relation to resistance to wear which becomes essential when using 3D-printed materials that must slide over the surface of another material [6]. FDM-produced parts are gradually replacing traditional components that are used in various industries, such as the aviation, locomotive, and health sectors [10]. The variables of the process and their configurations retain a significant influence on the mechanical properties of components printed by FDM [1, 5, 10]. Therefore, it is essential to assess the effects of input factors and predict results by using suitable process parameters in order to recover the mechanical properties of printed components. The combination of these characteristics is frequently challenging to understand, making FDM a complex process with many variables that affect material qualities and product quality [2, 8]. The quality and functionality of FDM printed items and printing characteristics, such as the orientation of the build, layer height, angle of the raster, width of the raster, air gap, filling density, and pattern, as well as rate of feed, have a significant impact on the outcomes [5, 11-13].

The status of mechanical qualities for functional fragments makes it imperative to investigate how process parameters affect mechanical performance [2, 14]. Therefore, more investigation is needed to identify printer parameters like filling density, layer height, and feed rate, especially in light of the paucity of available literature on the mechanical characteristics of objects produced by inexpensive 3D printers. Additionally, the investigation of the FDM process's impacts [15] on the criteria for mechanical performance is crucial when manufacturing continuous reinforced fiber 3D printed structures [16]. Numerous research studies havenow demonstrated how Layer height affects factors like surface quality, geometric correctness, production time,and expenses [17]. Polymer is the material most frequently employed for 3D printing, both for experimental and practical uses. Furthermore, due to its low cost, high adaptability, and straightforward process, fused deposition modeling, or FDM [18]. Is a popular additive manufacturing technique [7].

Leite et al. [2] used ANOVA statistical analysis to examine the mechanical qualities that are influenced by the four processing parameters, which include filling density, extrusion temperature, raster angle, and layer height. PLA 3D printed parts, toughness, modulus of elasticity, yield tensile strength, Ultimate Tensile Strength (UTS), and elongation at break have been tested.

Twenty-four experiments were conducted to assess the findings for all possible combinations of the factor levels. In Sagias et al. [19] study, the Taguchi approach was employed as an optimization tool. Using FDM 3D printing, the study aimed to improve the mechanical properties of the resulting ABS material. The researchers considered four factors in their work: layer height, printing pattern, printing force, and position, where each factor was considered to have three levels. The response variable was represented by the UTS. In the same vein, but for a somewhat different scenario, Wankhede et al. [20] applied Taguchi's approach. Filler density, layer height, support method, and ABS polymer samples are among the experimental input parameters to be investigated. In this perspective, some researchers have relied on Taguchi's L8-Orthogonal Range to determine the process parameters such as part manufacturing time and surface roughness to be measured. In addition, the process input variables have been determined. Dev and Srivastava [9] conducted an important study focusing on material consumption and compressive strength to improve the efficiency of the FDM process for fabricating lightweight high-strength parts through multi-objective FDM parameters.

It is evident from reading through the prior studies that the FDM process variables have a big influence on the mechanical characteristics of the printed components since these factors may be optimized by carefully choosing and adjusting them [21, 22]. Utilizing the Taguchi approach for experimental design and the ANOVA approach to maximize the goal functions, this study intends to assess the impact of three variables (Fill density, Layer height, and Printing speed) on the tensile property of 3D printed samples using ABS as the building material [23].

This research aims to optimize the FDM parameters to improve the mechanical properties of printed objects made of polymers. Until now, most of the research in this field has relied on experiments, with minimal emphasis on utilizing Design of Experiments (DOE) techniques to enhance the mechanical qualities of the finished fragments. Additionally, very few studies have explored the use of meta-heuristic algorithms to investigate 3D printing settings. The paper provides valuable insights into the combined effect of these three variables on FDM-manufactured components.

Through this work, the multifunctional FDM process' functionality may be improved, which can be utilized to satisfy FDM print design requirements more effectively by enhancing compressive characteristics, reducing the number of raw materials used, and speeding up printing times.

2. MATERIALS AND METHODS

2.1 Samples and materials

The examination samples are produced using the specified process parameters following the four procedures outlined in Figure 1. The sample preparation procedure was structured according to the previous methods [24-26].

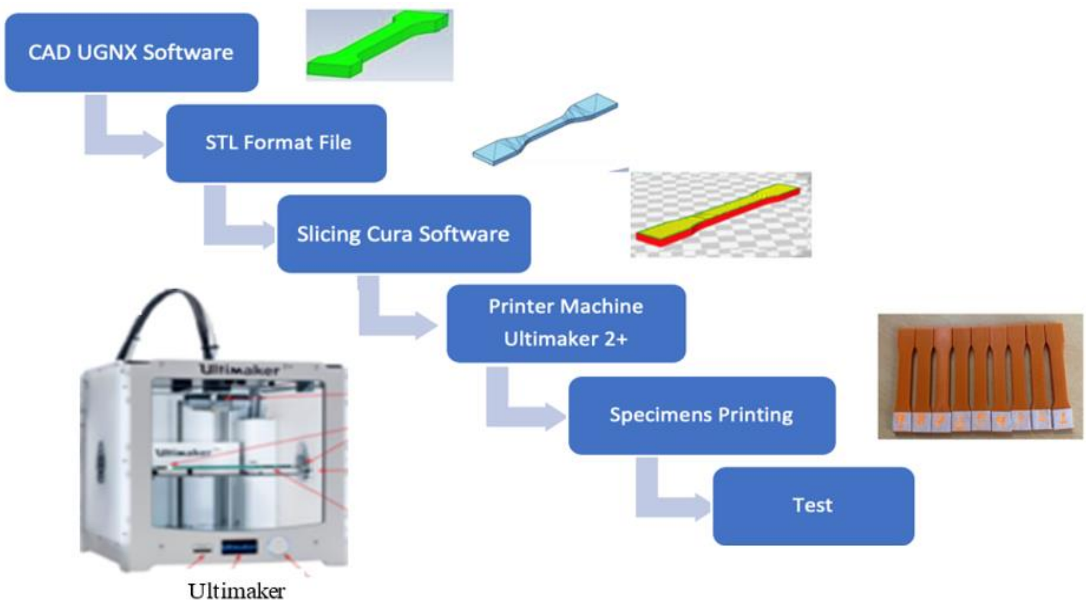

Figure 1. Steps of sample production

I. A three-dimensional (3D) model is formed using computer-aided design (CAD) software Figure 2 (a) and saved as a stereolithography file as a printable format (.stl) file.

II. The .stl file is subsequently transferred to a software package for operations (Cura 5), and customized groupings are established. At this phase, the portion is divided into slices at a specific height. At this stage, the parameter combinations, tool path generation, support generation, and contour curve writing are performed. This results in the development of a print-ready file, as depicted in Figures 2 (b) and (c).

III. The sample is created following the modification of the machine configuration, which involves modifying the building sheet and installing the necessary materials.

IV. The constructed prototype is extracted from the device, and the auxiliary material is eliminated, if necessary, as depicted in Figure 2 (d) and (e).

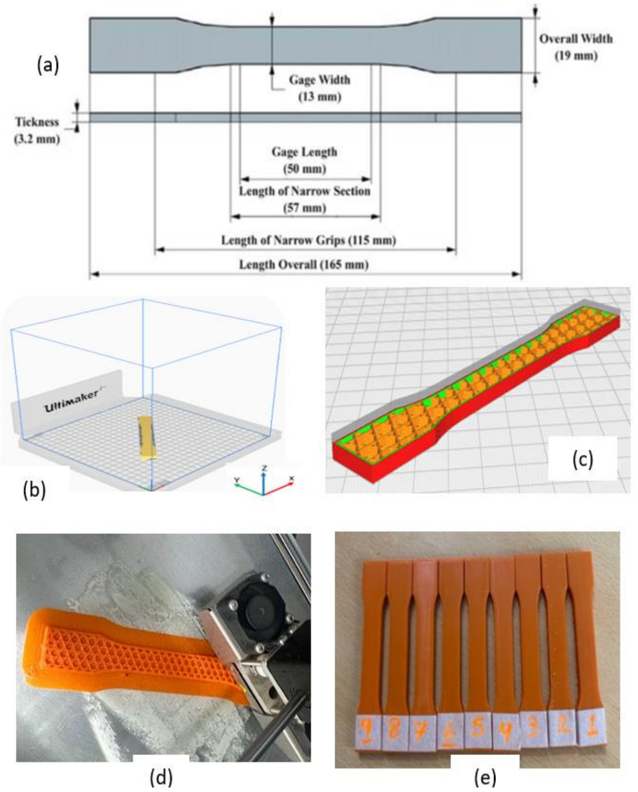

Figure 2. (a) The geometry tensile specimen ASTM D638 standard, (b) The specimen is placed on the 3D printer bed using Cura 5.5.0 software, (c) The process involves cutting samples, (d) Producing samples using an Ultimaker 2+ printer, and preparing the tensile specimen for examination, (e) Final samples.

2.2 3D printing

The samples utilized in this study were shaped with an Ultimaker 2+ 3D printer. The printer has a building envelope with dimensions of 210 mm by 210 mm by 205 mm, as depicted in Figure 3. It is capable of producing components with a precision of 0.2 mm. The research used Acrylonitrile Butadiene Styrene (ABS), which is the most often employed polymer in 3D printing, to fabricate components. ABS is a widely used thermoplastic compound with a specific chemical composition (C_8H_8)X, (C_4H_6)Y, and (C_3H_3N)Z) [18].

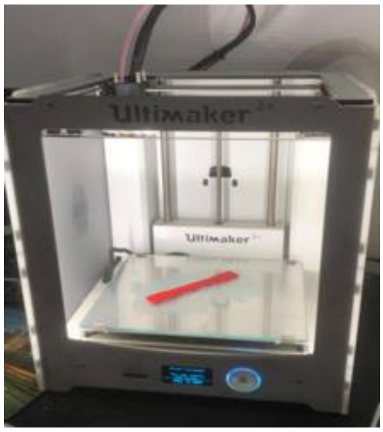

Figure 3. The machine Ultimaker 2+ 3D printer

2.3 Experimental design

The present investigation examines four key settings of the Ultimaker 2+ 3D printer to enhance and evaluate the correlation between these constraints and the recommended response characteristics. The selected parameters were layer height, filling density, and velocity of printing. The selection of input factors was based on the machine's specification, and the other characteristics are listed in Table 1.

Table 1. Process parameters and their respective ranges

Fixed Factors				
Factors	**Amount**			**Unit**
Filling-Pattern	Line			-
Thickness of the Shell-	0.2			mm
Orientation of the part-	45			degree
Size of the Nozzle (diameter)	0.6			mm
Temperature during Printing	230-260			°C
Build plate temperature levels	60			°C
Control Factors				
Factors	**Levels**			**Unit**
	1	**2**	**3**	
Printing velocity	35	65	95	mm/s
Layer height	0.15	0.2	0.25	mm
Filling density	30	50	70	%

Layer height refers to the vertical spacing between each layer that has been deposited, measured along the Z-axis, as the material flows from the nozzle tip of an FDM machine through extrusion. The size is often smaller than the extruder nozzle tips' diameter [21]. Filling density refers to the amount of material used to fill the space within a layer. This configuration can render a component completely or partially solid [22]. The primary factor that will impact the speed of 3D prints is the printing velocity. It controls the speed at which the printer's motors operate. This encompasses the motors that govern the X- and Y-axes, together with the motor responsible for the extruder [23].

2.4 Taguchi methods optimization

The Taguchi technique is a method that uses orthogonal arrays to organize the parameters and levels of a process. Taguchi established this experimental design, and it uses orthogonal arrays to determine how the process parameters should be adjusted [22]. The experimental outcomes are altered into signal-to-noise ratios (S/N ratios) to ensure the superiority of the process of production. In Table 2, the projected L9 orthogonal array and the outputs obtained through standard tensile testing of samples. The mechanical properties being evaluated are of maximization type, where the criterion "the larger, the better" is preferred as the guiding principle for the method of Taguchi. Eq. (1) represents the calculation of the signal-to-noise ratio(S/N):

$$\frac{S}{N} = -10 \ \log 1\Big/n \sum_{i=1}^{n} 1/Y_i^2 \qquad (1)$$

Let " n " be the orthogonal arrays' number, and "Y_i" represent the response variable. When selecting material for this study, choosing one with the highest tensile strength is advisable. The proportion of signal-to-noise (S/N) is a quantitative measure used to evaluate the performance of products and processes sensitive to noise. Optimal process parameter choices that result in the maximum signal-to-noise ratio always return superior quality with minimal variability [27-29]. This paper employed Taguchi methods using Minitab 16 software to determine the optimal configuration.

An experimental design of the matrix was developed using a Taguchi L9 mixed orthogonal array, which was determined by the input components and their respective levels. The details of the matrix can be found in Table 2.

Table 2. Experimental design matrix of L9 orthogonal array Taguchi

Filling Density %	Layer Height mm	Printing Velocity mm/s	No. of Experiment
30	0.15	35	1
30	0.2	65	2
30	0.25	95	3
50	0.15	65	4
50	0.2	95	5
50	0.25	35	6
70	0.15	95	7
70	0.2	35	8
70	0.25	65	9

2.5 Experimental procedure

The 3D-printed items were created using Cura software to help with the design process. The resulting design was stored as a .stl file and then imported into Insight, a specialized software for 3D printing [6]. For the purpose of assessing the strength of the material, a tensile test was conducted by placing the specimen into the grips of a testing device. The experiment followed the ASTM D638-03 standard [27] and employed a universal testing machine to measure tensile strength, as shown in Figure 4. During the test, the specimen was subjected to a strain rate of 5 mm/min and a load of 5 kN until it broke.

(a)

(b)

Figure 4. (a) Tensile Testing Machine, (b) Tensile specimens after testing

2.6 Validation analysis of variance

By analyzing sample variances, the analysis of variance (ANOVA) is a hypothesis-testing method that may be used to test the hypothesis that the means of three or more populations (or treatments) are equal. This expands upon the two independent samples t-tests.

The basis of ANOVA is a comparison of the variance (or variation) inside each sample and the variance between the data samples. The means of many samples will not be equal if the variance is significantly greater than the within variation. There will not be a discernible change in the sample means if the within and between variability are around the same size. ANOVA is used to compare treatments, analyze factors' impact on a variable, or compare means across multiple groups. Types of ANOVA include one-way (for comparing means of groups) and two-way (for examining the effects of two independent variables on a dependent variable).

3. RESULTS AND DISCUSSIONS

By employing Orthogonal Array (OA), the number of trials to be examined is greatly reduced, increasing the experimental efficiency. Table 3 displays the L9 Orthogonal Array and the tensile test data.

The best results of Ultimate strength (MPa), Young modulus (GPa), and Fracture strength (MPa) were observed with the increase of the Density of Infilling (%), with the increase of layer thickness (mm), there is consequently a decrease in printing velocity (mm/s). However, it plays a role in both very high and very low-speed values. It impacts the machine's vibration during manufacturing and the solidification time of the material as it passes through the nozzle, ultimately impacting the structural integrity of the component treated with FDM.

Table 3. Value of Mechanical properties and the orthogonal array

Exp Serial No.	Printing Velocity (S) (mm/s)	Height of Layer (LT) (mm)	Fracture Strength (MPa)	Young Modulus (GPa)	Ultimate Strength (MPa)	Density of Filling (ID) (%)
1	35	0.15	21.79	2.9	37.74	30
2	65	0.2	23.08	2.755	27.44	30
3	95	0.25	19.23	2.792	31.28	30
4	65	0.15	26.92	2.888	38.62	50
5	95	0.2	24.36	2.95	35.95	50
6	35	0.25	20.51	2.857	38.33	50
7	95	0.15	21.79	2.957	42.28	70
8	35	0.2	23.38	2.827	41.03	70
9	65	0.25	24.36	2.837	41.69	70

Taguchi's analysis approach has been adopted to investigate the effects on tensile strength. Table 4 shows the comparative impact of different factors on the variations in relative tensile strength. Our research indicates that the density of the filler material exhibits the most substantial influence on the tensile strength, with layer height and printing velocity being secondary factors.

Table 4. The response of signal-to-noise ratios for tensile strength

Levels	Filling Density %	Layer Height mm	Printing Velocity mm/s
1	18.78	21.99	21.26
2	21.49	20.42	21.18
3	22.57	20.43	20.4
Delta	3.79	1.57	0.86
Rank	1	2	3

Figure 5 presents the results and conclusions of The Taguchi method is used to analyze elongation, stress, elastic modulus, strength, and toughness values comprehensively. The graphs show the variations in tensile properties at different levels of printing variables. The influence of "filling density" on all outcomes is clearly noticeable. Based on the data in Table 4 and Figure 5, it is evident that the printing speed has a minimal effect on the tensile strength. Moreover, the results suggest that, aside from filling density, layer height also significantly impacts the tensile values. The findings indicate that increasing the filling density while decreasing the layer height improves the tensile strength, modulus of elasticity, and fracture strength of the PLA 3D-printed tensile test specimen. These plots are derived from tensile tests conducted on 3D-printed PLA material using the Taguchi method.

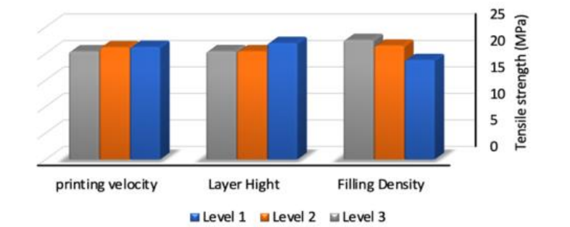

Figure 5. The signal-to-noise ratio (S-to-N ratio) of Tensile Strength

As the density of filling material increases, the structure of the specimen becomes more solid, leading to enhanced tensile strength. Figure 4 clearly demonstrates that the highest tensile strength is achieved at an infill percentage of 70%. The optimal route limits for achieving the highest UTS, modulus of elasticity, and strength of fracture are a filling density of 70%, a layer height of 0.15 mm, and a printing velocity of 35 mm/s.

Based on Figure 5, the thinnest layer with a thickness of 0.15 mm produces the uppermost tensile strength of 21.99 MPa. The tensile strength decreases to a minimum of 20.43 MPa when the layer thickness is 0.25 mm. Excessive stress application is the primary cause of failure in a tensile test. A decrease in layer thickness results in a more tightly packed specimen, enhancing bonding between the layers and consequently increasing tensile strength. Conversely, altering the thickness of the layers affects the density of the specimen. When the layers are less closely stacked, there is a reduction in tensile strength.

The experiment found that the speed at which the 3D printer operates does not directly affect the strength of the specimen. From experience, it could be realized that the strength of the sample is not directly affected by the speed of the 3D printer. In addition, the density of the material used and the height of each printed layer have a more direct effect than the printing speed. Higher printing speeds can cause the printer to vibrate, causing misaligned layers to move and producing uneven samples in the process. Conversely, when the printer runs at a very slow speed, it takes time for each layer to harden, which leads to weak adhesion between layers due to the low tensile strength when the printing speed is very slow.

3.1 ANOVA results of tensile strength

To determine the presence of significant differences in means across two or more variables. The ANOVA test represents a promising computational technique to address this by examining the variance. Identifying the process characteristics that have a significant and significant effect on the tensile strength is the importance of using the analysis of ANOVA [30], by dividing the overall variance of the tensile process test. By summing the squared differences from the overall mean, the final scale value of the composite parameters is represented relative to the individual contributions of each parameter. The results of the variance analysis for the tensile strength are presented in Tables 5, 6, and 7.

The research shows that the density of the filling has the most significant impact on tensile strength, followed by layer height and printing velocity.

Analysis of variance (ANOVA) has been performed to examine the results of the UTS and identify the key parameters affecting performance. Table 5 presents the ANOVA results for the average UTS with a confidence interval of 66.595%. The F-values from the ANOVA table are used to determine significance. A higher F-value indicates that adjusting a process parameter has a greater impact on performance characteristics.

Table 6 contains the ANOVA results for the Young Modulus at a confidence interval of 36.236%. The F values from the ANOVA table are used to assess the significance. The F-test assumes that increasing a process parameter will have a greater impact on performance characteristics when its F-value is larger.

Table 7 presents the ANOVA findings for the fracture strength at a confidence interval of 50.228%. The F-values from the ANOVA table are used to determine the significance of the data. The F-test assumes that increasing a process parameter will have a greater impact on performance characteristics when its F-value is larger.

Table 5. ANOVA table for ultimate tensile strength

Parameter	Squares Sum	Freedom' Degree	Mean of Squares	F-value	Influence (%)
Layer Height	2.224	2	1.112	0.786	17.92
Printing Velocity	1.923	4	0.481	0.340	15.49
Filling density	8.266	2	4.133	2.922	66.59
Error	0	2	0	0	0
Total	12.412	10			100

Table 6. ANOVA table for young modulus

Parameter	Squares Sum	Freedoms' Degree	Mean of Squares	F-value	Influence (%)
Layer Height	0.117	2	0.059	0.041	34.26
Printing Velocity	0.101	2	0.050	0.036	29.5
Filling density	0.124	4	0.031	0.022	36.24
Error	0.000	2	0	0	0
Total	0.342	10			100

Table 7. ANOVA table for fracture strength

Parameter	Squares Sum	Freedoms' Degree	Mean of Squares	F-value	Influence (%)
Layer Height	1.613	2	0.806	0.570	25.89
Printing Velocity	1.488	2	0.744	0.526	23.88
Filling density	3.129	4	0.782	0.553	50.23
Error	0	2	0	0	0
Total	6.230	10			100

4. CONCLUSIONS

This investigation implemented Taguchi's analysis technique to optimize the process parameters that influence the tensile strength of ABS specimens generated via FDM. The process variables examined in this research have an effect on the tensile strength of the specimen. The research findings yielded the following conclusions:

- The relationship between tensile strength and layer thickness is inversely proportional. As the thickness of the layer increases, there will be a decrement of tensile strength.
- A higher infill percentage significantly enhances tensile strength but results in higher material costs.
- The experimental assessments concluded that the printing speed is less significantly paralleled to the other two process factors.
- The study found that the best parameters for the process are a layer thickness of 0.15mm, a fill percentage of 70%, and a print speed of 35 mm/sec. When these settings were used, the specimen showed significant improvement in its mechanical performance, especially in terms of tensile strength. Additionally, there was a notable reduction in the time and materials required for production.
- The results of the ANOVA analysis show that the density of filling is the most significant factor among the input variables affecting the output responses, which are UTS, Young's Modulus, and Fracture Strength.

These findings suggest that it is possible to increase the strength and reliability of components produced using FDM. This study also provides valuable insights into the statistical significance of these process parameters.

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NOMENCLATURE

ABS	Acrylonitrile Butadiene Styrene
AM	Additive manufacturing
ANOVA	Analysis of variance
CAD	Computer-aided design
DOE	Design of Experiments
FDM	fused deposition modeling
OA	Orthogonal Array
PEEK	Polyether Ether Ketone
PLA	Polylactic Acid
S/N	signal-to-noise
UTS	Ultimate tensile strength

Greek symbols

n	orthogonal arrays' number
Y_i	response variable

Subscripts

ID	Density of Filling
LT	Height of Layer
S	Printing velocity