International Journal of Engineering and Artificial Intelligence

Journal home page: http://www.ijeai.com

Study on the effect of fused deposition modelling (FDM) process parameters on tensile strength and their optimal selection

Amanuel Diriba Tura[1*], Hana Beyene Mamo[2], Dommeti Kamalakara Rao[3]

[1,2,3] Faculty of Mechanical Engineering, Jimma Institute of Technology, Jimma, Oromia, Ethiopia

Corresponding Author: diriba.amanuel@ju.edu.et / amanueldiriba@gmail.com

Original article Received 30 April r 2021, Accepted 24 May 2021, Available online 1 June 2021

ABSTRACT

Additive manufacturing (AM), also known as 3D printing, is a transformative method to industrial fabrication that enables the creation of lighter, stronger parts and systems. Additive manufacturing uses data computer-aided-design (CAD) software or 3D object scanners to direct hardware to deposit material, layer upon layer, in precise geometric shapes. Fused deposition modeling (FDM) is one of the mainly used AM techniques for fabricating prototypes and functional parts in common engineering plastics. At various process parameters, mechanical properties of printed parts are significantly changed. Therefore, it is important to examine the influence of printing parameters on quality of printing part. This article provides an experimental investigation for the quality analysis of process parameters on printed parts using fused deposition modelling (FDM) in terms of tensile strength. The experiment were carried out using Taguchi's L9 orthogonal array technique by varying process parameters such Infill density, Infill pattern and Layer thickness using Acrylonitrile butadiene styrene (ABS) print material. Taguchi method are applied for the Multi-objective optimization of characteristics of Printing parts. ANOVA, S/N ratio, and 3D surface plot were used for analysis of experimental result and study the effect of process parameters. Results of Taguchi optimization indicates that the optimal FDM parameters for Tensile strength (UTS) are the layer height at 0.19mm, the Infill rate at 45 %, Build speed at 180 mm/min and the build temperature at 240 ºC which gives maximum UTS =39.094 MPa at maximum value of S/N ratio = 31.8422.

Keywords: Additive manufacturing , Fused deposition modeling; Tensile strength; ANOVA; Taguchi method.

1. Introduction

Additive Manufacturing (AM) technology, or more commonly known as 3D Printing, or Rapid Prototyping (RP), is a relatively new technology that emerged in the 1980s to create 3D objects. In 3D printing, parts produce 3D solid objects from a digital design. Typically, the final product is built by depositing materials in a layer-by-layer process without the use of traditional tools. You can use the PC software package to draw the desired part/object as a 3D object. AutoCAD and SolidWorks are the industry's most popular software platforms for designing complex prototypes for 3D printing applications. These 3D program files can be converted to the Stereolithography (STL) format, which is a format that 3D printers can understand(Abeykoon, Sri-Amphorn, & Fernando, 2020; Habibi & Ziadia, 2021; Krajangsawasdi, Blok, Hamerton, & Longana, 2021; Series & Science, 2021b, 2021a) .

Typical 3D printers have print nozzles that can be moved in three dimensions (x, y, z) and can handle single or multiple feeds. Parts are created layer by layer based on the 3D CAD model and its stereolithographic data. In general, 3D printed objects can provide a smooth surface with accurate dimensions using most of the cheaper 3D printers on the market. However, the manufacturer must carefully consider the printing parameters contained in each object to create a high-quality object (e.g., padding density, layer thickness, nozzle temperature setting, raster angle, etc.) (Fountas & Vaxevanidis, 2021; Omar, Razak, & Ab, 2021; Tura, Mamo, & Gemechu, 2021; Yadav, Chhabra, Kumar Garg, Ahlawat, & Phogat, 2020).

3D printing is widespread in a wide range of applications, and modern manufacturing wants to replace traditional technology with 3D printing if needed. 3D printing allows you to create complex objects in a single process step, eliminating production steps and reducing time to market, but with a slight increase in production costs. There are several techniques for 3D printing, including stereolithography (SLA), laser selective felt (SLS), 3D mapping, additive manufacturing (FDM), also known as additive filament manufacturing (FFF), and polyjet modeling . FDM is the most used 3D printing technology. The operating principle of FDM is mainly based on the concept of filament extrusion. Filament extrusion feeds molten plastic filament from an extrusion nozzle with a knurled feeder. The molten core is heated in the nozzle, melts to the specified temperature, and comes out in the form of small balls. The strands merged simultaneously and moved both horizontally and vertically, creating layer-by-layer deposits (Anas & Bhardwaj, 2020; Dong, Wijaya, Tang, & Zhao, 2018; Hu, Ng, Hau, & Chen, 2020; Naveed, 2020; Yosofi, Ezeddini, Ollivier, Lavaste, & Mayousse, 2021).

FDM was rapidly being used and the development of FDM cover a variety of sectors such as automotive, aviation, biomedicine etc. Several studies have been conducted to examine the impact of various print and post-processing parameters on the performance of print results using FDM. FDM has many advantages over other manufacturing method. Although FDM methods are widely used due to their many advantages, FDM methods also have some important weaknesses that are still of concern today. These weaknesses include poor mechanical properties, layer-by-layer appearance, poor surface quality, and a limited number of thermoplastics. Research and development to overcome these problems is certainly a challenge. Proper selection of printing parameters is important for producing high-quality 3D printed parts (Anoop & Senthil, 2020; Dave, 2020; Khan & Mishra, 2019; Pramanik, Mandal, & Kuar, 2019; Raykar & D'Addona, 2020; Wang, Zou, Xiao, Ding, & Huang, 2019). Many of the reported studies attempted to optimize the production parameters of fused deposition modeling (FDM) for printing high-quality parts.

(Mohamed, Masood, & Bhowmik, 2016) studied effects of the key FDM parameters (layer thickness, air gap, raster angle, building orientation, road width, and many contours) were investigated using the Q optimal response surface methodology. Effects on raw material consumption, construction times, and dynamic flexural modulus are critically examined. The study concluded that the most effective factors in terms of construction time, raw material consumption, and dynamic bending coefficient were layer thickness, air gap, construction direction, and many lines. However, raster angles and road widths are not very effective in terms of construction time and consumption of raw materials. The dynamic flex modulus is greatly enhanced by thick seams, zero air gaps, and 10 profiles.

(Cristian et al., 2017) 3D produced with a commercial 3D printer by running standard tensile tests and evaluating the effect of technical parameters on the mechanical properties of the print sample, taking into account different print orientations, fill rates, and fill patterns. Evaluate the tensile properties of molded components. The effect of the point angles is tested on samples designed with different crossed planes and printed with different angles such as 0 °, 30 °, 45 °, 90 °. Samples of 6 different fill patterns were tested with fill rates ranging from 20% to 100%. They found that the mechanical properties of the ABS samples produced by the melt deposition pattern presentation were affected not only by the expected infill rate but also by the printed pattern and orientation of the various layers and the shape of the local void. it would be strongly affected. Stress and deformation affect the overall mechanical behavior of the material.

(Rayegani & Onwubolu, 2014) A predictive data modeling group method was used to determine the functional relationship between process parameters and the tensile strength of a fusion deposition (FDM) modeling process. Preliminary tests were performing to determine if changes in segment orientation and raster line angle affect tensile strength. Both process parameters were finding to influence the tensile force response. Further experiments were performed when the process parameters considered were the orientation of the segment, the angle of the raster, the width of the raster, and the air gap. Process parameters and experimental results were introduced into the Group Data Processing Method (GMDH) to produce the expected output. It turns out that the expected output value is closely related to the measured value. Using differential evolution (DE), it was founded that optimal process parameters achieve good reactivity at the same time. They improved the function of the additive manufacturing parts produced by improving the process parameters.

(Chacón, Caminero, García-Plaza, & Núñez, 2017) Investigated the effects of structural orientation, layer thickness, and feed rate on the mechanical performance of PLA samples produced with low-cost 3D printers. Three-point tensile and flexural tests are performed to determine the mechanical response to the printed sample. They concluded from this study that the edge samples showed optimal mechanical performance in terms of strength, hardness, and ductility, ductility decreased with increasing layer thickness and straight samples Tensile and flexural strength decreases with increasing feed speed, minimum printing time is required: thickness was recommend for high layers and high feed rates.

(Prasada, Rajiv, & Geethika, 2019) Investigated the effects of FDM variables, namely layer thickness, print temperature, and fill pattern on the tensile strength of PLA carbon fibers. The printing process takes into account the three levels of each variable and a complete factorial design was performed for the experiment (33). The tensile test data were analyzed by performing ANOVA and the results show that the interaction between the fill pattern of the layer thickness and the extrusion temperature of the fill pattern has a significant effect on the tensile strength. The maximum tensile strength of 26.59 MPa was achieved with a layer thickness of 0.1 mm, an extrusion temperature of 225 ° C, and a cubic fill pattern.

2. Materials and methods

2.1 Flash forge creator pro machine specification

Flash forge creator pro as shown in Figure 1, is used to produce the specimens. This machine is developed and marketed by Stratasys. The machine has a large build chamber volume (227x148x150mm). It incorporates multiple materials like ABS, PLA and uses Water Works soluble support for ABS. Support material use can be easily breakaway by hand. It can build part in three available layer height that is 0.180mm, 0.290mm, and 0.40mm. The creator pro has an enclosure and two fans blowing air out of the box when the nozzle fan is activated. A heated bed is featured as well as a double extruder configuration. Table 1 shows FDM machine specifications.

Figure 1: Flash forge creator pro

Table 1: FDM machine specification

Printing specification	
Number of extruder	2
Print technology	Fused filament fabrication
Screen	LCD Panel
Build volume	227×148×150mm
Layer resolution	0.05-0.4mm
Build precision	±0.2mm
Positioning precision	Z axis 0.0025mm;XY axis 0.011mm
Filament diameter	1.75mm(±0.07)
Nozzle diameter	0.4mm
Build speed	10-200mm/sec
Software	Flash print
AC input	100V-240V/4.5A-2.5A
Connectivity	USB Cable, SD Card
NET Weight	14.8kg

2.2 ABS Material

Acrylonitrile Butadiene Styrene (ABS) chemical formula ($C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$) is a common thermoplastic. ABS is a copolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The advantage of ABS is that this material combines the strength and rigidity of the acrylonitrile and styrene polymers with the toughness of the polybutadiene rubber. The most important mechanical properties of ABS are impact resistance and toughness. In this paper, ABS material is used to fabricate parts.

2.3 Experimentation setup: Selection of parameter

Some of the main flash forge variable parameters are considered in this research to evaluate the correlation between these parameters and the proposed response characteristics. Four factors layer height(A), infill density (B), build speed (C), and build temperature (D) varied each at three levels, as shown in Table 2 are considered. Other factors are kept at a fixed level as shown in Table 1.

Table 2: Process parameters to be controlled

Factors	**symbol**	**unit**	**Level 1**	**Level 2**	**Level 3**
Layer height	A	mm	0.180	0.290	0.40
Infill density	B	%	15	30	45
Build speed	C	mm/sec	60	120	180
Build temperature	D	℃	220	240	260

2.4 Design of experiment

Design of experiment is a systematic and scientific way of planning the experiments, collection, and analysis of data with limited use of the available resource. The DOE approach helps to study many factors simultaneously and most economically by studying the effects of individual factors on the result, the best factor combination can be determined. Since the design of the experiment using Taguchi’s provides an efficient plan to study the experiments, with a minimum amount of experimentation, it was chosen for performing the FDM variable process parameters experiments. Based on selected cutting process parameters and their levels an experimental design matrix was constructed in Table 3 using Taguchi L9 orthogonal array (three levels-four factors) were selected depends on several factors and their levels. Each experimental trial in the design consists of a combination of different FDM parameters with different levels and is used to measure tensile strength (UTS). Part fabricated using FDM is shown in figure 2.

Table 3: Experimental data obtained from the L9 orthogonal array

EXP. trials	**Input parameters**			
	Laser height mm	Infill density %	Build speed mm/sec	Build Temperature ^{o}C
1	0.180	15	60	220
2	0.180	30	120	230
3	0.180	45	180	240
4	0.290	15	60	220
5	0.290	30	120	230
6	0.290	45	180	240
7	0.40	15	60	220
8	0.40	30	120	230
9	0.40	45	180	240

Figure 2: Parts fabricated by FDM machine

2.6 Methods of Measurement and Testing

The tensile strength of the material is defined as the maximum stress that the material can sustain under uniaxial tensile loading. The ability of composite material to withstand forces that pull it apart is analyzed by its tensile strength, basically stating the extent to which the material will stretch before breaking. The load-indicator zero and the plot-load-axis zero, if applicable, should be set before the specimen is placed in the grips. Then the specimen placed in the grips by proper alignment and specimen tabs should be fully engaged by closing the grips. One of the crossheads is fixed at one end and another end is move uniaxial, the peak force (load at break) measured. The tensile tests were carried out using a cystometric material testing machine with 350 KN maximum capacity, The crosshead speed of this machine is 1mm/min and the test stops once the specimens are broken. The material used for specimen preparation is ABS with a nominal thickness of 8 mm, width 12 mm, and the tensile strength is calculated by dividing maximum load(load at break) with an original cross-sectional area(original width × original thickness). Figure 3 shows testometric and tensile testing specimens to predict the influence of FDM parameter settings on tensile strength.

$$Tensile\ strength\ (UTS)\ =\frac{Breaking\ load(Pf)}{(orignal\ cross\ sectional\ area(Ao)}\quad \text{…………. .Equation 1}$$

Figure 3: Testometric Machine and tested specimen

2.7 Methods of analysis

To investigate the relationship between variable parameters and the outcome response, several analysis methods should be followed. In this research work, various analysis methodologies were used to relate the response compressively. Taguchi analysis, Signal to Noise ratio (S/N ratio), and analysis of variance (ANOVA) was used for analysis and optimization of experimental result. Main effect plots, Interaction plots, 3D Surface plots, and Contour plots were also plots using Minitab (V 18.1) software to study the relationship between process parameters and outcome results.

3. Result and Discussion

In this section, tensile strength results are analyzed and improved using the Taguchi method. Effects of process parameters such as: improves layer height, infill density, build speed and build temperature for parts manufactured with FlashForge FDM machines. Analysis variance, main effect plots, interaction diagrams, 3D and counter plots are generated using Minitab and origin software to analyze the relationships between each process parameter.

3.1 Result of Tensile strength

The tensile test is performed on a test material tester with a maximum capacity of 350 KN, the crosshead speed of the machine is 1 mm / min, and the test is stopped when the sample is destroyed. The material used to prepare the sample was ABS with a nominal thickness of 5 mm and a width of 12 mm, and the tensile strength was the maximum load (load at break) in the original cross-sectional area (original width x original width). It is calculated by dividing. thickness. Table 4 shows the results of the tensile strength (UTS) for each of the 9 trials. The S / N share was calculated using the MINITAB V18 experimental software.

Table 4: Experimental results for Tensile strength (UTS) and S/N ratio

Run	Layer height mm	Infill %	Build speed mm/min	Build temperature ºC	UTS MPa	S/N ratio
1	0.180	15	60	220	21.945	26.8267
2	0.180	30	120	230	35.934	31.1101
3	0.180	45	180	240	39.094	31.8422
4	0.290	15	60	220	30.383	29.6526
5	0.290	30	120	230	38.952	31.8106
6	0.290	45	180	240	23.964	27.5912
7	0.40	15	60	220	36.715	31.2969
8	0.40	30	120	230	34.946	30.8679
9	0.40	45	180	240	28.743	29.1706

3.2 Taguchi analysis for Tensile strength (UTS)

The results of tensile strength were analyzed using the Taguchi method. Table 5 shows the ranking of various factors in terms of their relative importance to the relative changes in tensile strength. We find that pollutant density is the most important factor affecting tensile strength (UTS), followed by build speed, build temperature, and layer height.

Table 5: Response table for Tensile strength (UTS)

Levels	Layer height mm	Infill %	Build speed mm/min	Build temperature ºC
1	32.32	29.68	26.95	29.88
2	31.10	36.61	31.69	32.20
3	33.47	30.60	38.25	34.81
Delta	2.37	6.93	11.30	4.93
Rank	4	1	2	3

3.3 Analysis of variance for Tensile strength (UTS)

Tensile strength (UTS) results were analyzed using ANOVA to determine key factors influencing performance measurements. Table 6 shows the average tensile strength (UTS) ANOVA results for each 95% confidence interval. The F and P values shown in the ANOVA table are used to confirm the significance. The principle of the F-test and P-test is that the larger the F-number and the smaller the value of a particular parameter, the greater the impact of this process parameter change on performance characteristics. A P-value of less than 0.0500 (that is, $\alpha = 0.05$, or a 95% confidence level) indicates that the term process parameter is significant. The mean tensile strength ratio (UTS) ANOVA tables show that the P-values of 0.048, is less than 0.05 for the infill density, this shows that infill density is the significant factor that affects the mean Tensile strength (UTS).

Table 6: Analysis of Variance for means Tensile strength (UTS)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer height	2	8.417	4.208	0.07	0.931
Infill	2	84.990	42.495	1.74	0.048
Build speed	2	43.31	21.654	1.13	0.329
Build temperature	2	11.78	5.892	0.05	0.741
Error	4	2.599	0.5199		
Total	12	151.096			

3.4 Main effect and interaction plot of Tensile strength (UTS)

Figure 4 shows the main effects of the average tensile strength (UTS). It is clear that the tensile strength (UTS) decreases as the layer height increases to 0.29 mm, but after this point, the tensile strength (UTS) begins to increase. In other cases, increasing the infill rate increases tensile strength (UTS), but begins to decrease above 30%. Tensile strength (UTS) increases with increasing construction speed. In another case, UTS increases with the increasing Build temperature. Figure 5 shows the interaction of process parameters with tensile strength (UTS).

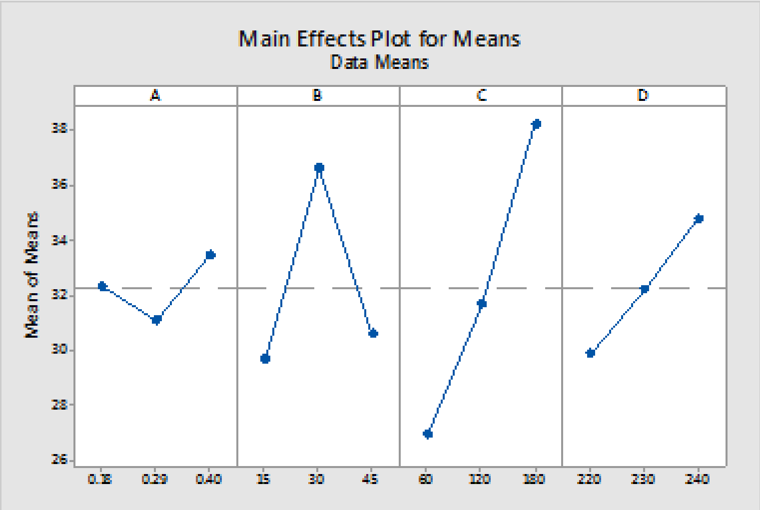


Figure 4: Main effect plot for mean oTensile strength (UTS)

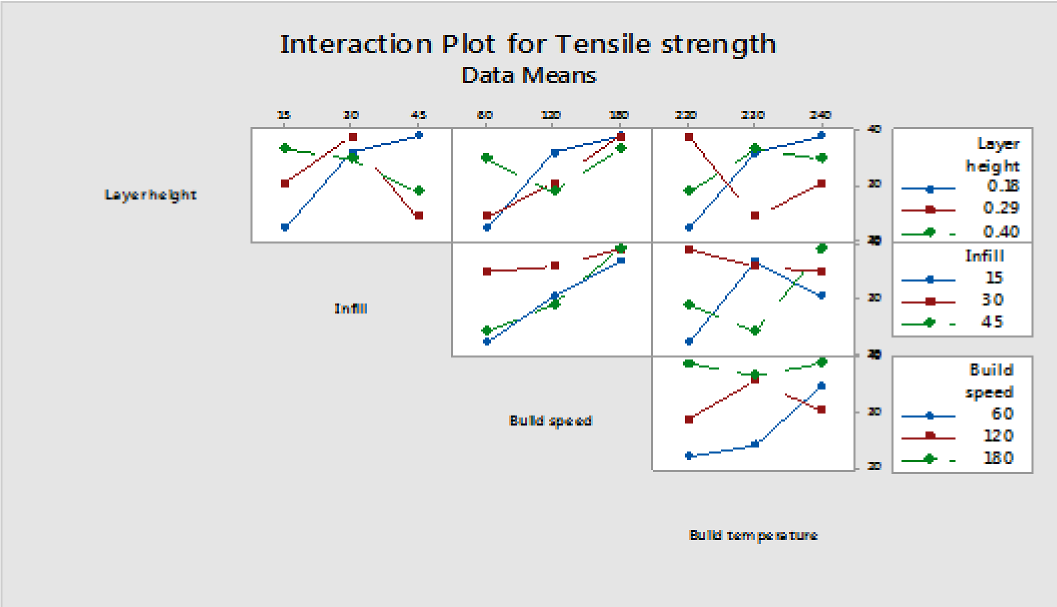
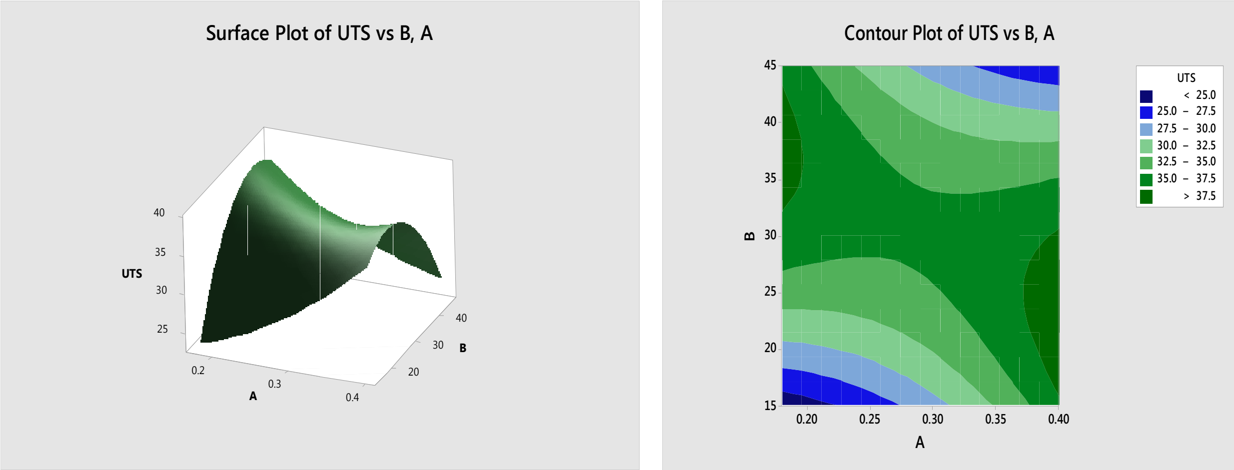


Figure 5: Interaction plot for Ra means with all process parameters

3.5 3D Surface and Contour plot for Tensile strength

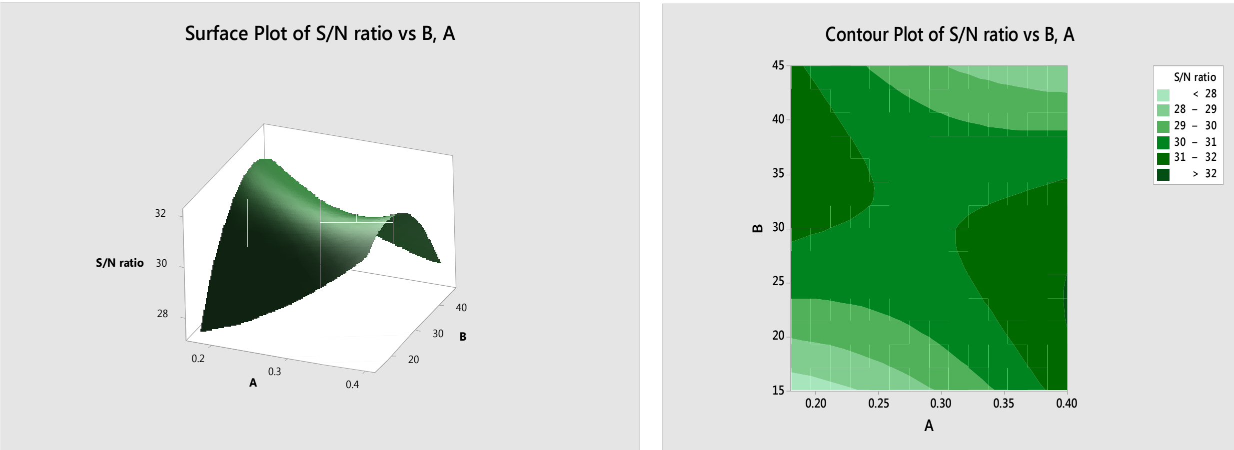
3D surface and contour plots are plots of the tensile strength (UTS) vs. layer height, filling, build speed, and build temperature, creating an analysis of the relationships between each process parameter. Figure 6(a-b) shows a 3D surface and contour diagram of the interaction analysis between infill and layer heights relative to average tensile strength. From this plot, higher tensile strengths are observed at layer heights of 0.20 mm to 0.25 mm, and it is clear that infill of 35% to 40% at the bottom layer and infill height results in lower tensile strengths. Therefore, the optimum average can be obtained from the tensile strength at lower layer heights and higher fill factor values.



(a) (b)

Figure 6: (a-b): 3D Surface and contour plots of Tensile strength against Infill and Layer height

Figure 7(a-b) shows the 3D surface and contour plot of the interaction analysis between infill and layer height for the S/N ratio of Tensile strength. From this plot, it is clearly shown that the higher S/N ratio of Tensile strength is observed at layer height between 0.20 mm and 0.25 mm, and Infill between 35 % and 40 %. At lower layer height and Infill, the S/N ratio of Tensile strength was lower. Therefore, optimum means Tensile strength can be obtained at the lower layer height and higher infill rate value.



(a) (b)

Figure 7(a-b): 3D Surface and contour plots for S/N ratio of Tensile strength against Infill and Layer height

After a complete analysis of the 3D surface and contour plot of the interaction, we can predict that at Layer height between 0.20mm to 0.25 mm and infill between 35 % to 40% could yield the best Tensile strength (maximum tensile strength). It can be summarized that to obtain a higher tensile strength, it is recommended to use a low Layer height between and high infill.

3.6 Response optimization Tensile strength

There are three conditions for improvement using the Taguchi method. Smaller is better, nominal is better, larger is better. For this tensile strength (UTS), the larger one is best. The signal-to-noise ratio is used to measure performance for developing noise-sensitive products and processes. Process parameter settings with the highest signal-to-noise ratio always provide optimum quality with minimal contrast. Based on S / N analysis, the optimal process parameters for tensile strength (UTS) are layer height at level -1, infill rate at level -3, build speed at level -3, and build speed at level -3. Table 7 shows Optimum setting parameters for Tensile strength (UTS).

Table 7: Optimum response tables for Tensile strength (UTS)

Factors	Code	Level	Optimize value	
Layer height	A	1	0.180 mm	**Optimum Value UTS =39.094 MPa At maximum value of S/N ratio = 31.8422**
Infill	B	3	45 %	
Build speed	C	3	180 mm/min	
Build temperature	D	3	240 ºc	

3.7 Validation of optimum setting

Experiments were conducted to ensure optimum performance, and the results are shown in Table 6.7. The results show that the improved conditions provide good tensile strength (UTS). The initial tensile strength reading was UTS = 39.094MPa. After setting the parameters to the optimized values, the response characteristics changed to UTS = 39.783MPa.

Table 8: Results of the confirmation experiments for optimized condition of mean UTS

Optimal level	Response obtained		Error % = 1.732 %
	Initial reading (predicted result)	**After reading** (Exp. result)	$= \frac{(\textbf{Exp. Result} - \textbf{predicted result})}{\textbf{\textit{Experimental result}}}$
Mean Tensile strength (UTS)	39.094 MPa	39.783 MPa	

4. Conclusion

This paper introduces Taguchi methods for improving the tensile strength (UTS) of parts manufactured on FDM flash forging machines. The Taguchi design was used for the L9 orthogonal matrix experiment for experiment. The effects of process parameters such as Analyze layer height, padding, build rate and build temperature of response products using Taguchi analysis, main effects plots, interaction plots, 3D surface plots, and contour plots using Minitab V18.1 software. The resulting signal-to-noise ratio was used to determine the optimal setting and the following conclusions were drawn for tensile strength (UTS):

- Tensile strength (UTS) is highly affected by Build speed followed by infill, build temperature, with little effect on layer height.
- The result of Taguchi optimization is that the optimal FDM parameters for tensile strength (UTS) are layer height at level 1, infill rate at level 3, build speed at level 3, and build temperature at level 3. It shows that.
- The optimum tensile strength (UTS) value by the Taguchi method is UTS = 39.094 MPa, and the maximum ratio is S / N = 31.8422.

Acknowledgment

Special thanks to Jimma Institute of Technology, Jimma University, and Addis Ababa University, Ethiopia for allowing us to carry out all the necessary experiments and validations of the model.

Reference

Abeykoon, C., Sri-Amphorn, P., & Fernando, A. (2020). Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed structures. *International Journal of Lightweight Materials and Manufacture*, *3*(3), 284–297. https://doi.org/10.1016/j.ijlmm.2020.03.003

Anas, M. K. M., & Bhardwaj, H. R. N. (2020). Effect of FDM process parameters on mechanical properties of 3D ‑ printed carbon fibre – PLA composite. *Progress in Additive Manufacturing*, (0123456789), 1–7. https://doi.org/10.1007/s40964-020-00145-3

Anoop, M. S., & Senthil, P. (2020). Materials Today : Proceedings Microscale representative volume element based numerical analysis on mechanical properties of fused deposition modelling components. *Materials Today: Proceedings*, (xxxx). https://doi.org/10.1016/j.matpr.2020.08.469

Chacón, J. M., Caminero, M. A., García-Plaza, E., & Núñez, P. J. (2017). Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection. *Materials and Design*, *124*, 143–157. https://doi.org/10.1016/j.matdes.2017.03.065

Cristian, D., Engineering, M., Engineering, M., Ph, R. L., Engineering, M., & Engineering, M. (2017). *Effects of raster orientation,infill rate and infill pattern on mechanichal properties of 3D printed materials* (Vol. LXIX). Romania.

https://doi.org/10.1515/aucts-2017-0004

Dave, H. K. (2020). *Lecture Notes in Mechanical Engineering Advances in Manufacturing Processes*.

Dong, G., Wijaya, G., Tang, Y., & Zhao, Y. F. (2018). Optimizing process parameters of fused deposition modeling by Taguchi method for the fabrication of lattice structures. *Additive Manufacturing*, *19*, 62–72. https://doi.org/10.1016/j.addma.2017.11.004

Fountas, N. A., & Vaxevanidis, N. M. (2021). Optimization of fused deposition modeling process using a virus-evolutionary genetic algorithm. *Computers in Industry*, *125*, 103371. https://doi.org/10.1016/j.compind.2020.103371

Habibi, M., & Ziadia, M. (2021). From gantry-based machine to robot-based fused deposition modelling : A state-of-the-art, (April). https://doi.org/10.20944/preprints202104.0203.v1

Hu, C., Ng, W., Hau, J., & Chen, W. (2020). The fabrication of long carbon fiber reinforced polylactic acid composites via fused deposition modelling : Experimental analysis and machine learning. https://doi.org/10.1177/0021998320972172

Khan, M. S., & Mishra, S. B. (2019). Minimizing surface roughness of ABS-FDM build parts: An experimental approach. *Materials Today: Proceedings*, *26*, 1557–1566. https://doi.org/10.1016/j.matpr.2020.02.320

Krajangsawasdi, N., Blok, L. G., Hamerton, I., & Longana, M. L. (2021). Fused Deposition Modelling of Fibre Reinforced Polymer Composites : A Parametric Review.

Mohamed, O. A., Masood, S. H., & Bhowmik, J. L. (2016). Mathematical modeling and FDM process parameters optimization using response surface methodology based on Q-optimal design. *Applied Mathematical Modelling*, *40*(23–24), 10052–10073. https://doi.org/10.1016/j.apm.2016.06.055

Naveed, N. (2020). Investigate the effects of process parameters on material properties and microstructural changes of 3D-printed specimens using fused deposition modelling (FDM). *Materials Technology*, *00*(00), 1–14. https://doi.org/10.1080/10667857.2020.1758475

Omar, M. H., Razak, A., & Ab, N. (2021). electrodes based upon polymers / carbon nanomaterials using a fused deposition modelling (FDM) method as emerging electrochemical sensing devices, 16557–16571. https://doi.org/10.1039/d1ra01987b

Pramanik, D., Mandal, A., & Kuar, A. S. (2019). An experimental investigation on improvement of surface roughness of ABS on fused deposition modelling process. *Materials Today: Proceedings*, *26*, 860–863. https://doi.org/10.1016/j.matpr.2020.01.054

Prasada, V. D., Rajiv, P., & Geethika, V. N. (2019). Materials Today : Proceedings Effect of fused deposition modelling (FDM) process parameters on tensile strength of carbon fibre PLA. *Materials Today: Proceedings*, *18*, 2012–2018. https://doi.org/10.1016/j.matpr.2019.06.009

Rayegani, F., & Onwubolu, G. C. (2014). Fused deposition modelling (FDM) process parameter prediction and optimization using group method for data handling (GMDH) and differential evolution (DE). *Int J AdvManuf Technol*, *2*, 1–11. https://doi.org/10.1007/s00170-014-5835-2

Raykar, S. J., & D'Addona, D. M. (2020). Selection of Best Printing Parameters of Fused Deposition modeling using VIKOR. *Materials Today: Proceedings*, *27*, 344–347. https://doi.org/10.1016/j.matpr.2019.11.104

Series, I. O. P. C., & Science, M. (2021a). Optimization Of Process Parameters In 3d Printing-Fused Deposition Modeling Using Taguchi Method Optimization Of Process Parameters In 3d Printing – Fused Deposition Modeling Using Taguchi Method. https://doi.org/10.1088/1757-899X/1112/1/012009

Series, I. O. P. C., & Science, M. (2021b). Recent Progress of Fused Deposition Modeling (FDM) 3D Printing : Constructions , Parameters and Processings Recent Progress of Fused Deposition Modeling (FDM) 3D Printing : Constructions , Parameters and Processings. https://doi.org/10.1088/1757-899X/1096/1/012045

Singh, T. H. B., Chohan, J. S., & Kumar, R. (2019). Performance analysis of vapour finishing apparatus for surface enhancement of FDM parts. *Materials Today: Proceedings*, *26*, 3497–3502. https://doi.org/10.1016/j.matpr.2020.04.553

Tura, A. D., Mamo, H. B., & Gemechu, W. F. (2021). Mathematical modeling and parametric optimization of surface roughness for evaluating the effects of fused deposition modeling process parameters on ABS material. *International Journal of Advanced Engineering Research and Science (IJAERS) ISSN:*, *6495*(5), 49–57. https://doi.org/10.22161/ijaers

Wang, P., Zou, B., Xiao, H., Ding, S., & Huang, C. (2019). Effects of printing parameters of fused deposition modeling on mechanical properties , surface quality , and microstructure of PEEK. *Journal of Materials Processing Tech.*, *271*(February), 62–74. https://doi.org/10.1016/j.jmatprotec.2019.03.016

Wankhede, V., Jagetiya, D., Joshi, A., & Chaudhari, R. (2019). Experimental investigation of FDM process parameters using Taguchi analysis. *Materials Today: Proceedings*, *27*, 2117–2120. https://doi.org/10.1016/j.matpr.2019.09.078

Yadav, D., Chhabra, D., Kumar Garg, R., Ahlawat, A., & Phogat, A. (2020). Optimization of FDM 3D printing process parameters for multi-material using artificial neural network. *Materials Today: Proceedings*, *21*, 1583–1591. https://doi.org/10.1016/j.matpr.2019.11.225

Yosofi, M., Ezeddini, S., Ollivier, A., Lavaste, V., & Mayousse, C. (2021). Evaluation of environmental , technical , and economic indicators of a fused deposition modelling process, *2*(March), 3–7. https://doi.org/10.36756/JCM.v2.3.7