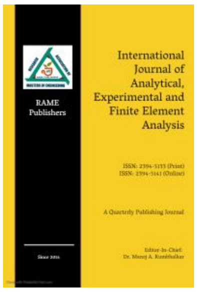

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Effect of FDM Process Parameters on the Mechanical Properties and Production Costs of 3D Printed PowerABS Samples

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***Abstract*—The main objective of this study is to analyze of the effect of fused deposition modelling (FDM) printing process parameters on the mechanical properties, printing times and production costs of samples printed with Power Acrylonitrile Butadiene Styrene (PowerABS) filament using a three-dimensional (3D) printer. This study is primarily focused on the effects of the mechanical properties of 3D samples subjected to the influence of three factors; layer thickness (0.15, 0.2, and 0.25 mm), raster angle (15, 45, and 75^0), table orientation (flat, horizontal, and vertical). For the experiment study, analytical methods such as regression analysis, variance analysis (ANOVA), Signal / Noise (S / N) ratio were used to determine the effect of FDM printing parameters on the mechanical properties with Taguchi optimization method. The results showed that 45° raster angle the highest mechanical properties at each individual layer when compared to 15° and 75°. The results also found tensile strength to directly proportionate to layer thickness. As observed in the results, by improving the material properties, it will be possible to provide support for mechanical engineers and designers to reduce printing time, filament material use and printing costs.**

***Keywords*—** FDM, mechanical properties, optimization, PowerABS, production cost, Taguchi

I. Introduction

Additive manufacturing (AM) is a method for printing products directly with desired properties using various materials to create a three-dimensional (3D) product. Although the usage area of this method is becoming widespread day by day, it is used in different sectors for different purposes. The development of 3D samples with high quality, production time, and low cost are a key issue to remain competitive [1-3]. Many experimental studies are in progress to improve the mechanical properties of the printed products by fused deposition modelling (FDM) method-based production technology [4-7]. In the literature, researches have been conducted to determine the tensile strength and modulus of elasticity of PLA (Polylactic acid) and ABS (Acrylonitrile butadiene styrene) produced with a 3D printer [7]. In the other study, they investigated to determine the influence of FDM printing parameters on the mechanical properties of samples printed with ABS [8]. It has been shown in studies that the raster angle and table orientation, which is one of the printing parameters used in the 3D printing process, affects the thermal properties and mechanical properties of the printed products [9]. Studies have been carried out to determine the

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appropriate 3D printing process parameters and improvements have been achieved on the mechanical properties of the printed products [4-6]. In a study conducted with the FDM method, the effect of different raster angles (0, 30, 45, 60 and 90°) and table orientation in different directions (horizontal and vertical) on the mechanical properties were investigated and the tensile strength, flexural strength, production of the products printed from ABS. It has been determined that printing parameters such as duration, cost, and raster angle affect surface roughness and mechanical properties [2]. In addition, regarding the dimensional stability for products printed with the FDM method, the orthogonal array L9 Taguchi method has optimized the dimensional accuracy and printing parameters of products printed from PLA and ABS materials [10]. In addition, optimum printing parameters with the Taguchi method; Occupancy rate (20, 50 and 70 %), layer thicknesses (0.1, 0.2 and 0.3 mm), and the number of outer perimeter layers (1, 2 and 3) are determined varyingly. its dimensional accuracy has been improved [11]. In recent years, AM emerged as a powerful technology able to support these new approaches using different materials for the development of prototype products [12]. AM was defined as the "process of joining materials to make objects from the 3D model, usually layer by layer, as opposed to subtractive producing technologies" [13]. FDM was attracted an increasing attention due to his inherent simplicity, versatility, and low cost. The 3D part is built by lowering the platform along the Z (vertical) axis to print the successive layers on top of the previous ones [14]. ABS is one of the most globally used materials in FDM being easily available and providing parts with good quality, resilience, and durability [15]. In order to fulfil the final sample specifications, it is crucial to predict the mechanical properties of obtained parts and materials, understanding how FDM printing parameters affects these properties [16]. Even if the number of works based on experimental methods and design of experiments such as Taguchi method, full factorial designs, or ANOVA, aiming to study the effect of the FDM process parameters on the quality of produced parts [17].

Tensile tests for plastic materials are commonly applied according to ISO 527 standards. 3D printers are computer aided manufacturing (CAM) since they are faster than traditional manufacturing methods, nowadays almost every industrial area such as automotive, aerospace, medical, manufacturing, education purpose use 3D printers. Changes in the material and printing parameters affect the mechanical properties of printed samples. Tensile and izod impact tests are the most important inspection methods to mechanical properties of the filament materials [4-6]. Mechanical characteristics of 3D products materials must be known for proper manufacturing.

In this study, the modified ABS (PowerABS) filament material, which is widely used in FDM method today, It was aim to analyze of the effect of FDM process parameters on the mechanical properties, printing times and costs of products printed with PowerABS filament using a 3D printer. This study is primarily focused on the effects of the mechanical properties of 3D products subjected to the influence of three factors; layer thickness (0.15, 0.2, and 0.25 mm), raster angle (15, 45, and 75^0), table orientation (flat, horizontal, and vertical).

II. MATERIAL AND METHOD

A. 3D Printing process parameters and PowerABS filament material

This study aims to investigate the effects of three important parameters such as layer thickness (0.15, 0.2, and 0.25 mm), raster angle (15, 45, and 75^0), table orientation (Flat-F, Horizontal-H, and Vertical-V) on the mechanical properties of 3D printed samples using with PowerABS filament in FDM method. For this purpose, process input and output parameters were shown as schematically in Figure 1.

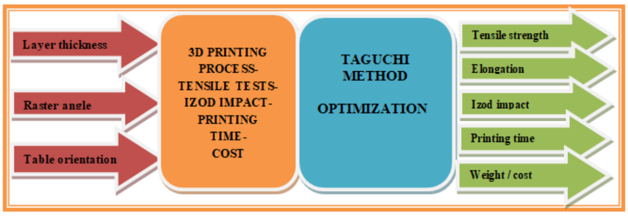

Figure 1. Process input and output parameters

Experiment samples were designed using the SolidWorks program and transferred to the Slic3r program, which is the slicing interface program in STL format. After, the G-code was created; it was sent to the printer with a USB connection and printed on a 3D model platform. Printing parameters of the samples were determined as shown in Table 1.

TABLE I.

FDM PRINTING PROCESS PARAMETERS

No	FDM printing process parameters	
	Features	Values
1	Filament diameter (mm)	1.75
2	Filament type	Power ABS
3	Nozzle diameter (mm)	0.40
4	Extruder temperature (°C)	240
5	Bed temperature (°C)	80
6	Occupancy rates (%)	10
7	Extrusion width (mm)	0.35
8	Layer thickness (mm)	0.15, 0.2, 0.25
9	Printing speed (mm/min)	4200
10	Speed in free (mm/min)	4800
11	Room temperature (°C)	24 ± 1
12	Filling structures	Rectilinear
13	Model	Rigid3D Zero2
14	Printing Volume	200*200*200 mm
15	Machine Dimension	390*460*460 mm
16	Tolerance	0.05 - 0.3 mm
17	Power	600 W
18	Extruder nozzle	1
19	Processor	Arduino processor

PowerABS filament material was used and the physical and chemical properties of the filament material are shown in Table 2.

TABLE II

THE PROPERTIES OF POWERABS FILAMENT MATERIAL [18]

Filament Material	PowerABS
Filament color	Black
Filament diameter (mm)	1.75
Density (g / cm³)	1.04
Strength (MPa)	51
Elastic modulus (MPa)	2750
Percentage elongation (%)	30
Melting point (ºC)	235
Heat deflection temperature (ºC)	94

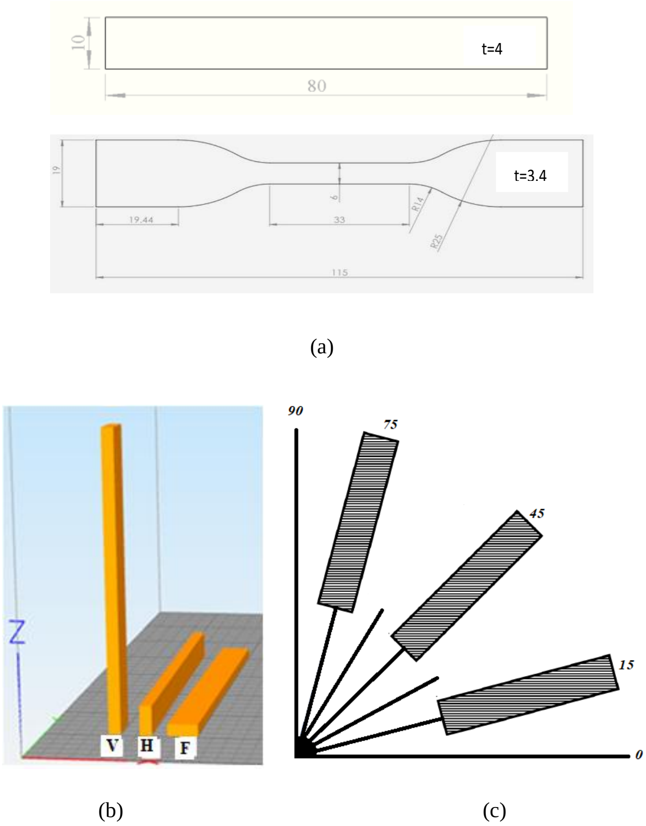

Figure 2 Tensile test and izod samples dimensions (a), View of the table orientations (b) , Raster angles (c)

Tensile test and izod samples dimensions (a), Printing orientations (b), and raster angles (c) were given in Figure 2. Printing orientations (Flat -F, Horizontal-H, and Vertical-V) and raster angles (15, 45, and 75^0) were schematically shown in Figure 2.

B. *Tensile tests and Izod impact tests*

Tensile tests were carried out in UTEST brand 10-ton tensile testing device in department of Mechanical Engineering Laboratory. Tensile tests were carried out at a tensile test speed of 5 mm / min and under equal conditions for each test sample.

Izod impact tester, Standard Izod (ISO 180) test samples (80x10x4 mm), and tensile test device were shown in Figure 3.

Figure 3. Tensile tests and Izod impact test devices

C. Taguchi Method and Printing process parameters

Establishing the correct experimental design is important for the accuracy of the results obtained in experimental studies. In this study, Taguchi L_9 orthogonal was used as the experimental setup and result analysis method. In this approach, a statistical performance measure known as the Signal / Noise (S / N) ratio is used to analyze the results. "S" in this ratio refers to the signal ratio and "N" refers to the noise ratio. Noise sources are all variables that cause the performance characteristics to be obtained to deviate from the target value. In calculating S / N ratios, nominal is the best, largest is the best and smallest is the best methods depending on the characteristic type are used. Since this study is desired to have mechanical properties, which is considered as quality characteristic, the “largest is the best”, approach is taken into account in calculating S / N ratios. The equation given in equation 1 was used to calculate the S / N ratios. The “smallest is the best”, approach is taken into account in calculating S / N ratios. The equation given in equation 2 was used to calculate the S / N ratios. Here; “y_i” represents the measured mechanical properties value, “I” refers to the observation value, “n” refers to the experiments valid for this study. Control factors and levels are given in Table 3. The Taguchi method is one of the most widely used optimization methods [19, 20]. In this context, the L_9 sequence was chosen because the parameters were limited.

Taguchi L_9 experiment design is given in Table 4.

$$S / N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} 1/y_i^{2}\right) \quad (1)$$

$$S / N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^{2}\right) \quad (2)$$

In Equation (1), y_i is the measured mechanical properties values; n is the number of experiments performed.

TABLE III.

PRINTING PROCESS PARAMETERS AND LEVELS

Experiment No	Control factors		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

TABLE IV.

TAGUCHI L_9 EXPERIMENT DESIGN

Symbol	Factors	Unit	Levels	Output
A	Layer thickness	mm	0.15 0.2 0.25	Tensile strength, Elongation values Izod impact values
B	Raster angle	0	15 45 75	
C	Orientation		Flat- F Horizontal-H Vertical-V	

III. RESULTS AND DISCUSSION

Experimental design was carried out according to the Taguchi L_9. The effect of the 3D printing process parameters on the mechanical properties was determined with an ANOVA analysis. The results obtained from the tests were estimated with a regression analysis. The standard tensile test samples were printed, tensile tests were performed, and the tensile strength, elongation, and izod impact values obtained from mechanical tests were averaged. Average tensile strength, elongation, and izod impact values S / N (signal /noise) ratios are given in Table 5. Picture of test samples after breaking was shown in Figure 4. From the Figure 4, it can be seen that table orientation is the most important process parameters for elongation rates (%). Other parameters (layer thickness and raster angle) have affected damages less than table orientation. And also, it can be seen that the table orientation has inverse proportion with elongation rate. The table orientation of Horizontal (H) gives the high tensile strength values. It was observed that the table orientation of H gives more strength than other table orientation (F and V). Other table orientations caused the samples more brittle and decrease the elongation of samples. The 45 degree of raster angle gave the most optimum results. The 15 and 75 degrees of raster angle made the samples more brittle. Percentage elongation (%) of the samples is much reduced according to the Figure 4.

TABLE V.
TAGUCHI L_9 ORTHOGONAL ARRAY, EXPERIMENTAL RESULTS AND THEIR S/N RATIOS

No	Average Tensile strength values (MPa)	S/N (dB)	Average Elongation values (%)	S/N (dB)	Average Izod impact values (kj/m²)	S/N (dB)
1	13.293	22.4725	0.024	-32.3958	4.059	12.1684
2	3.380	10.5783	0.040	-27.9588	5.489	14.7899
3	16.353	24.2719	0.007	-43.0980	1.175	1.4008
4	4.673	13.3919	0.029	-30.7520	6.167	15.8015
5	14.306	23.1104	0.006	-44.4370	1.506	3.5565
6	5.940	15.4757	0.030	-30.4576	4.995	13.9707
7	17.783	25.0001	0.005	-46.0206	1.956	5.8274
8	16.056	24.1127	0.033	-29.6297	8.995	19.0800
9	13.293	22.4725	0.025	-32.0412	10.284	20.2432

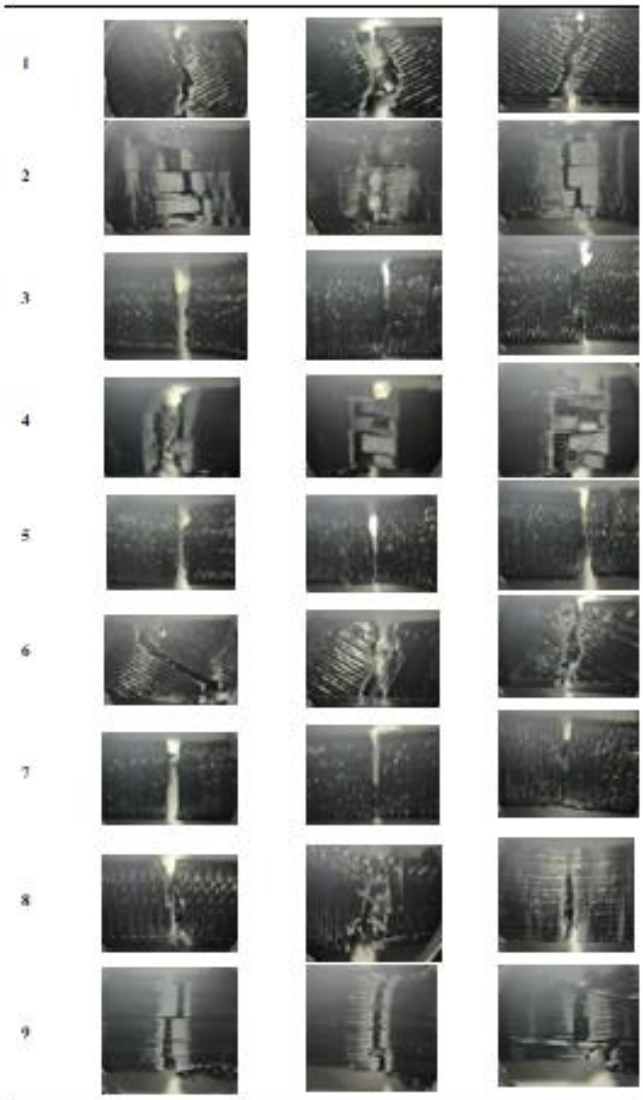

Figure 4. Picture of test samples after breaking

A. Analysis results of tensile strength values

Analysis of variance (ANOVA) results were given in Table 6. According to the ANOVA results, all parameters were statistically significant. The main effect plot for the effects and levels of the printing process parameters was shown in Figure 5. It is desired to have high mechanical properties in 3D printing process. The larger is better calculation for calculating the S / N ratio was carried out using the Minitab18 program. The optimized process parameters and their corresponding order obtained from analysis results were given in Table 6 and Table 7.

Linear Regression Equation is given in (2) for estimation of tensile strength at 95% confidence interval (CI).

Regression Equation (3);

$$\text{Estimated Tensile Strength (MPa)} = 12.02 + 42.6\,(A) + 0.0062\,(B) - 4.74\,(C) \quad (3)$$

Optimum estimated tensile strength value was obtained as 13.469 MPa according to the equation (3).

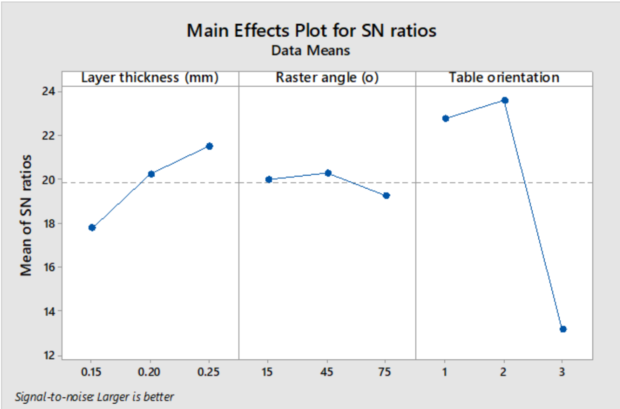

Figure 5. S / N rates for tensile strength

TABLE VI.

ANALYSIS OF VARIANCE FOR S/N RATIOS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer thickness (mm)	2	28.060	14.030	3.96	0.202
Raster angle (°)	2	1.676	0.838	0.24	0.809
Table orientation	2	202.675	101.338	28.62	0.034
Error	2	7.081	3.541		
Total	8	239.493			

TABLE VII.

RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS

Levels	A Layer thickness (mm)	B Raster angle (°)	C Table orientation
1	17.78	20.01	22.80
2	20.26	20.29	23.62
3	21.53	19.27	13.15
Delta	3.75	1.02	10.47
Rank	2	3	1

In table 7 gives that the most important factors for the strength were the filling structures occupancy rates, and layer thickness. The results obtained from tensile tests were confirmed by the ANOVA. The optimum tensile strength for the FDM process parameter using PowerABS filament was obtained at third level (A_3) of filling structures, at second level (B_2) of raster angle, and at second level (C_2) of table orientation (Figure 5).

In Figure 5, the main effect plot for S/N ratios for tensile strength and FDM processing parameters were shown. The optimum tensile strength of determined for the printing process parameters (table orientation, layer thickness, and raster angle) were 2 (H), 0.25 mm, and 45°, respectively. The optimum 3D printing process parameters was given in Table 8.

TABLE VIII.

OPTIMUM PRINTING PARAMETERS FOR HIGHEST TENSILE STRENGTH VALUE

Layer Thickness (mm)	Raster angle (°)	Table orientation
0.25	45	2 (H)

The surface plot graphs of tensile strength were shown in Figure 6. In these surface plot graphs, as the layer thickness increased, the tensile strength values increased proportionally. The 45 degree of raster angle gave the most optimum results. The 15 and 75 degrees of raster angle made the samples more brittle and fragile. Percentage elongation (%) of the samples is much reduced.

The table orientation of Horizontal (H) gives optimum tensile strength values. It was observed that the table orientation of H gives more strength than other table orientation (Flat - F and Vertical - V). Other table orientations caused the samples more brittle and decrease the elongation of samples. It has shown similar results in the literature [23-29].

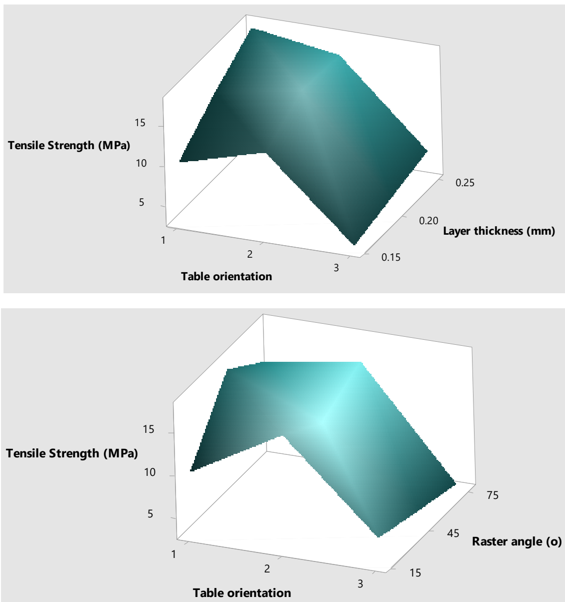

Figure 6. Surface plot of tensile strength

B. Analysis results of elongation values

The results of ANOVA for elongation values were shown in Table 9. According to these results, table orientation was statistically significant. The main effect plot for the effects and levels of the 3D printing process parameters was shown in Figure 7. It was desired to have high mechanical properties in 3D printing process. The optimized 3D printing process parameters and their corresponding order obtained from analysis results are given in Table 10 and Table 11. Linear Regression Equation is given in (3) for estimation of elongation value at 95 % confidence interval (CI).

Regression Equation (4);

$$\text{Estimated Elongation (\%)} = 0.0494 - 0.0267\,(A) + 0.000022\,(B) - 0.01150\,(C) \quad (4)$$

Optimum estimated elongation value was obtained as 0.0025 (%) according to the equation (4).

TABLE IX.
ANALYSIS OF VARIANCE FOR SN RATIOS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer thickness (mm)	2	0.000012	0.000006	0.16	0.859
Raster angle (o)	2	0.000083	0.000041	1.18	0.459
Table orientation	2	0.001176	0.000588	16.75	0.056
Error	2	0.000070	0.000035		
Total	8	0.001341			

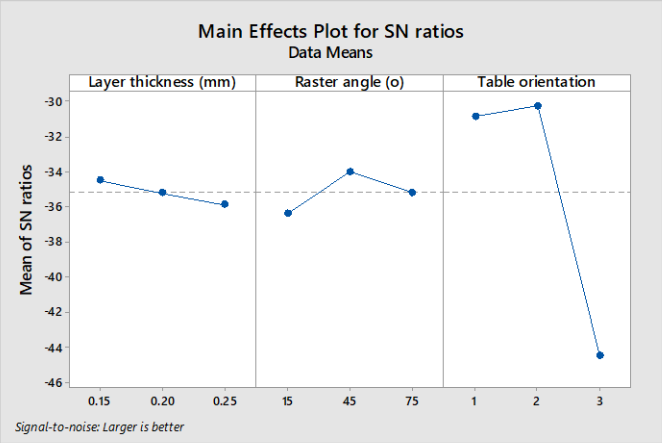

Figure 7. S / N rates for elongation

TABLE X.
RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS

Levels	Layer thickness (mm)	Raster angle (o)	Table orientation
1	-34.48	-36.39	-30.83
2	-35.22	-34.01	-30.25
3	-35.90	-35.20	-44.52
Delta	1.41	2.38	14.27
Rank	3	2	1

In table 11 shows that the most important factors for the elongation values were the 3D printing process parameters (layer thickness, raster angle, and table orientation). The experimental results of tensile tests were confirmed by the ANOVA. The optimum elongation value for the FDM process parameter was obtained first level (A_1) of filling structures, at second level (B_2) of raster angle, and at second level (C_2) of table orientation (Figure 10).

The main effect plot for S/N ratios for elongation values and 3D printing process parameters were shown in Figure 7. The optimum elongation value of determined for the 3D printing process parameters (table orientation, raster angle, and layer thickness) were 2 (H), 45° and 0.15 mm, respectively.

TABLE XI.
OPTIMUM 3D PRINTING PARAMETERS FOR HIGHEST ELONGATION

Layer thickness (mm)	Raster angle (°)	Table orientation
0.15	45	2 (H)

The surface plot graphs of elongation values were shown in Figure 8. In these surface plot graphs, as the layer thickness was not very effective in elongation values. The optimum elongation value was found with layer thickness (0.15 mm), raster angle (45°), and table orientation (Horizontal) of the samples. The 15 and 75 degrees of raster angle made the samples more brittle and elongation (%) of the samples is much reduced. It has shown similar results in the literature [23-29].

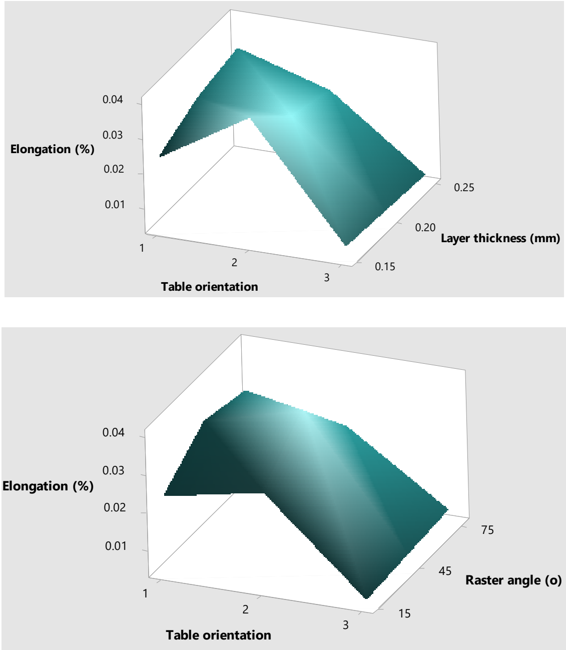

Figure 8. Surface plot of elongation

C. Analysis results of izod impact values

The results of ANOVA were given in Table 12. According to the ANOVA results, table orientation was statistically significant. The main effect plot for the effects and levels of the 3D printing process parameters is given in Figure 9. It was desired to have high mechanical properties in 3D printing process. The optimized process parameters and their corresponding order obtained from analysis results are shown in Table 13 and Table 14. Linear Regression Equation is given in (4) for estimation of izod impact value at 95% confidence interval (CI).

Regression Equation (5);

Estimated izod value (kj/m²) = 1.35 + 35.0 (A) + 0.0237 (B) - 2.24 (C) (5)

Optimum estimated izod impact value was obtained as 5.667 kj/m² according to the equation (5).

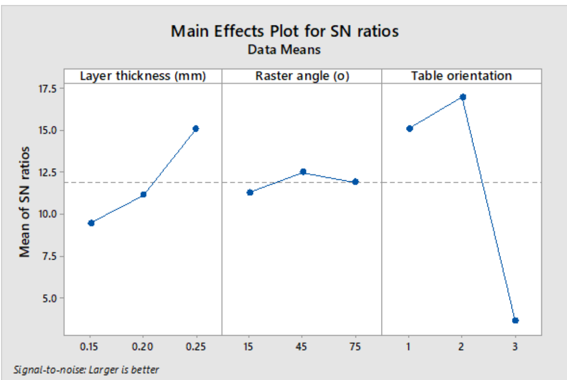

Figure 9. S / N rates for izod impact values

TABLE XII.

ANALYSIS OF VARIANCE FOR SN RATIOS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer thickness (mm)	2	20.853	10.427	6.94	0.126
Raster angle (^{0})	2	3.663	1.831	1.22	0.451
Table orientation	2	54.935	27.468	18.28	0.052
Error	2	3.005	1.503		
Total	8	82.456			

TABLE XIII.

RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS (IZOD IMPACT TESTS)

Levels	(A) Layer thickness (mm)	(B) Raster angle (°)	(C) Table orientation
1	9.453	11.266	15.073
2	11.110	12.475	16.945
3	15.050	11.872	3.595
Delta	5.597	1.210	13.350
Rank	2	3	1

In table 13 shows that the most important factors for the mechanical properties (izod impact values) were the printing process parameters (layer thickness, raster angle, and table orientation). The optimum izod impact value for the 3D printing process parameter was obtained at third level (A_3) of layer thickness, at second level (B_2) of raster angle, and at second level (C_2) of table orientation.

The main effect plot for S/N ratios for izod impact values and 3D printing process parameters were shown in Figure 12. The optimum izod impact value of determined for the 3D printing process parameters (table orientation, layer thickness, and raster angle) were 2 (H), 45°, 0.25 mm, respectively (Table 14).

TABLE XIV.

OPTIMUM 3D PRINTING PARAMETERS FOR IZOD IMPACT VALUE

Layer Thickness (mm)	Raster angle (°)	Table orientation
0.25	45	2 (H)

The surface plot graphs of izod impact values were given in Figure 10. In these surface plot graphs (raster angle-table orientation and layer thickness – table orientation), the results of izod impact tests and analysis were shown similarities in results of the tensile strength. As the layer thickness increased, the tensile strength values increased proportionally. The 45 degree of raster angle and table orientation (2) were given the most optimum results of izod impact value. The 15 and 75 degrees of raster angle made the samples more brittle. Percentage elongation (%) of the samples is much reduced. It was observed that the table orientation of H gives more izod impact values than other table orientation (Flat - F and Vertical - V). Other table orientations caused the samples more brittle and decrease the elongation of the samples.

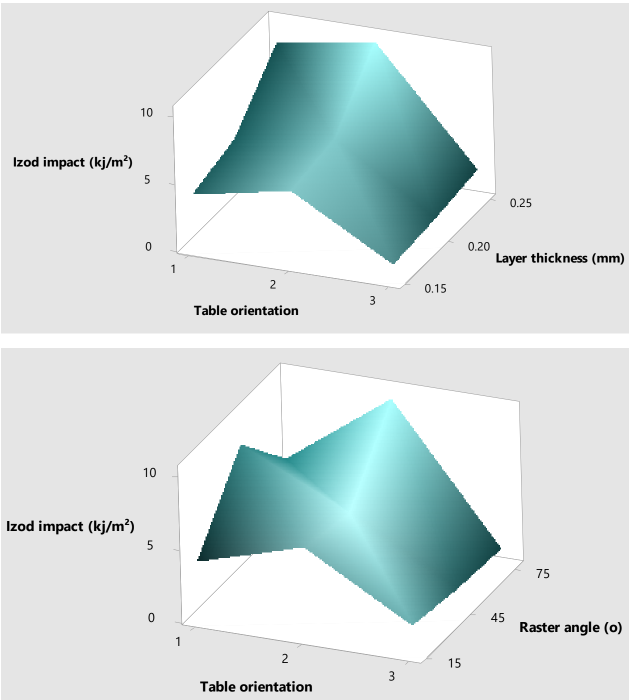

Figure 10. Surface plot of izod impact values

D. The analysis results of printing times and product weight values

The experimental results of printing times - product weight values for all three samples and their S/N ratios were given in Table 15. The lowest printing time sample 8 was also obtained as 50 minute (min) and the lowest sample weight sample 1 was also obtained as 9.22 gr.

TABLE XV.

TAGUCHI L_9 ORTHOGONAL ARRAY, EXPERIMENTAL RESULTS AND THEIR S/N RATIOS

No	Printing time (min)	S/N (dB)	Sample weight (%)	S/N (dB)
1	68	-36.6502	9.22	-19.2946
2	90	-39.0849	11.02	-20.8436
3	98	-39.8245	11.27	-21.0385
4	75	-37.5012	12.37	-21.8474
5	69	-36.7770	10.08	-20.0692
6	56	-34.9638	9.96	-19.9652
7	59	-35.4170	11.21	-20.9921
8	50	-33.9794	10.89	-20.7406
9	61	-35.7066	12.51	-21.9451

Determining the effects of FDM process parameters on the costs of products is of great importance. The 3D samples can be produced with various possible printing orientations. The table orientation influences the prototype printing time, filament material, and accuracy. Most of the time, 3D parts are required to be print with the fastest speeds and the lowest costs, provided the quality requirements are fixed at a certain level. An appropriate table orientation ensures optimum utilization of the resources and reduces the cost. Costing is one of the major areas of improvement in 3D printing process [21, 22]. Optimal part orientation can be one of the methods of solving part accuracy problems [23]. Determination of the optimum table orientation and minimizing the production costs were identified as two of the most basic problems for all laminated 3D printing processes [24].

The results of ANOVA were given in Table 16. The main effect plot for the effects and levels of the 3D printing process parameters is given in Figure 11. It was desired to have low printing process time by FDM method. The optimized process parameters obtained from analysis results are shown in Table 17 and Table 18. Linear

Regression Equation is given in (6) for estimation of 3D printing process time value at 95% confidence interval (CI).

Regression Equation (6);

$$\text{Time (min.)} = 106.3 - 286.7\,(A) + 0.072\,(B) + 8.67\,(C) \qquad (6)$$

Optimum estimated printing time value was obtained as 86.035 min. according to the equation (6).

TABLE XVI.

ANALYSIS OF VARIANCE FOR S/N RATIOS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer thickness (mm)	2	1270.22	635.11	11.45	0.080
Raster angle (°)	2	28.22	14.11	0.25	0.797
Table Orientation	2	600.89	300.44	5.42	0.156
Error	2	110.89	55.44		
Total	8	2010.22			

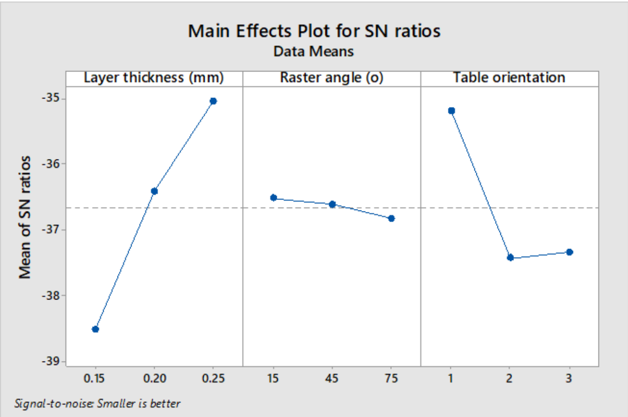

Figure 11. S / N rates for printing process time values

TABLE XVII.

RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS (PRINTING PROCESS TIME)

Levels	Layer thickness (mm)	Raster angle (o)	Table orientation
1	-38.52	-36.52	-35.20
2	-36.41	-36.61	-37.43
3	-35.03	-36.83	-37.34
Delta	3.49	0.31	2.23
Rank	1	3	2

In table 17 shows that the most important factors for the 3D printing process time were the printing process parameters (layer thickness, raster angle, and table orientation). The optimum printing time for the 3D printing process parameter was obtained at first level (A_1) of layer thickness, at third level (B_3) of raster angle, and at second level (C_2) of table orientation.

The main effect plot for S/N ratios for printing time values and 3D printing process parameters were shown in Figure 11. The optimum printing time value of determined for the 3D printing process parameters (layer thickness, table orientation, and raster angle) were 0.15 mm, 2 (H), 75°, respectively (Table 18).

TABLE XVIII.

OPTIMUM 3D PRINTING PROCESS PARAMETERS FOR PRINTING TIME

Layer Thickness (mm)	Raster angle (°)	Table orientation
0.15	75	2 (H)

The surface plot graphs of printing time values were given in Figure 12. In these surface plot graphs (raster angle-table orientation and layer thickness-raster angle), as the layer thickness increased the printing time values increased proportionally. The 75 degree of raster angle and table orientation 2 (H) were given the most optimum results of 3D printing time value.

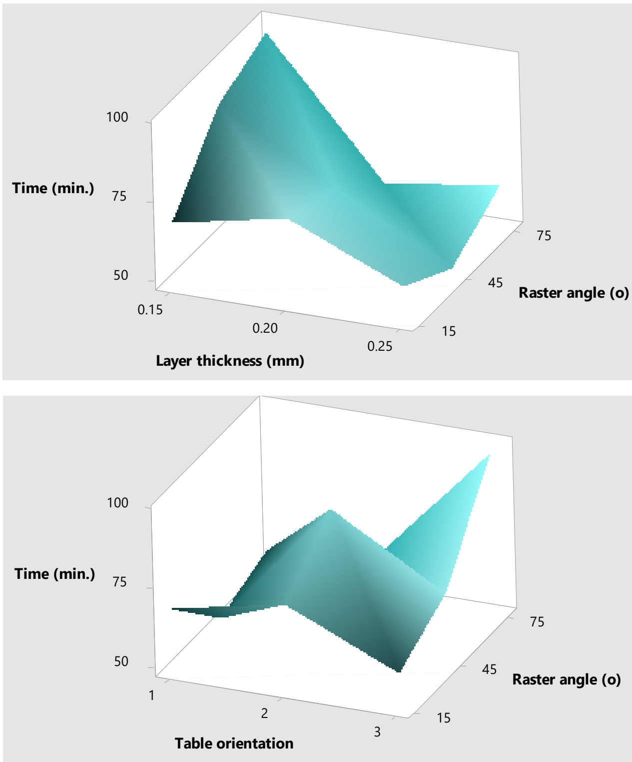

Figure 12. Surface plot of 3D printing time values

The results of ANOVA were given in Table 19. The main effect plot for the effects and levels of the 3D printing process parameters is given in Figure 13. It was desired to have low product weight and printing costs. The optimized process parameters obtained from analysis results are shown in Table 20 and Table 21. Linear Regression Equation is given in (6) for estimation of product weight and printing costs value at 95% confidence interval (CI).

Regression Equation (7);

$$\text{Weight (gr)} = 7.82 + 10.33\,(A) + 0.0052\,(B) + 0.415\,(C) \qquad (7)$$

Optimum estimated product weight value was obtained as 11.622 gr according to the equation (7).

TABLE XIX.

ANALYSIS OF VARIANCE FOR S/N RATIOS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer thickness (mm)	2	1.6956	0.8478	1.17	0.460
Raster angle (°)	2	0.5114	0.2557	0.35	0.739
Table orientation	2	5.7050	2.8525	3.94	0.202
Error	2	1.4465	0.7232		
Total	8	9.3584			

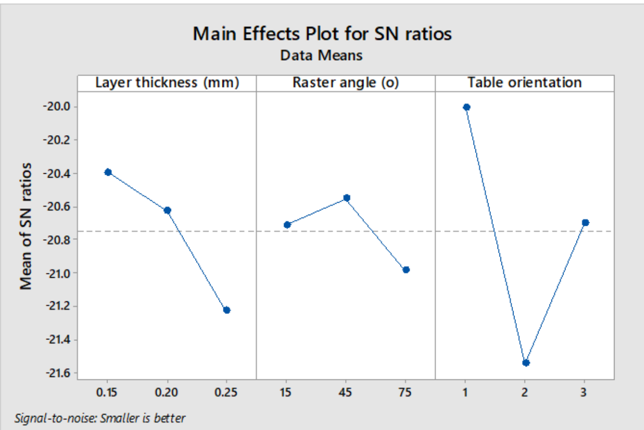

Figure 13. S / N rates for product weight values

In table 20 shows that the most important factors for the product weight were the printing process parameters (layer thickness, raster angle, and table orientation). The optimum product weight for the 3D printing process parameter was obtained at third level (A_3) of layer thickness, at third level (B_3) of raster angle, and at second level (C_2) of table orientation.

The main effect plot for S/N ratios for product weight values and 3D printing process parameters were shown in Figure 13 and Table 21. The optimum product weight value of determined for the 3D printing process parameters (table orientation, layer thickness, and raster angle) were 2 (H), 0.25 mm, and 75°, respectively (Table 20).

TABLE XX.

OPTIMUM 3D PRINTING PROCESS PARAMETERS FOR PRODUCT WEIGHT

Layer Thickness (mm)	Raster angle (°)	Table orientation
0.25	75	2 (H)

TABLE XXI.

RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS (PRODUCT WEIGHT)

Levels	Layer thickness (mm)	Raster angle (°)	Table orientation
1	-20.39	-20.71	-20.00
2	-20.63	-20.55	-21.55
3	-21.23	-20.98	-20.70
Delta	0.83	0.43	1.55
Rank	2	3	1

The surface plot graphs of product weight values were given in Figure 14. In these surface plot graphs (raster angle-table orientation and layer thickness-table orientation), as the layer thickness increased the product weight values increased proportionally. The 75 degree of raster angle and table orientation 2 (H) were given the most optimum results of 3D product weight (cost) value.

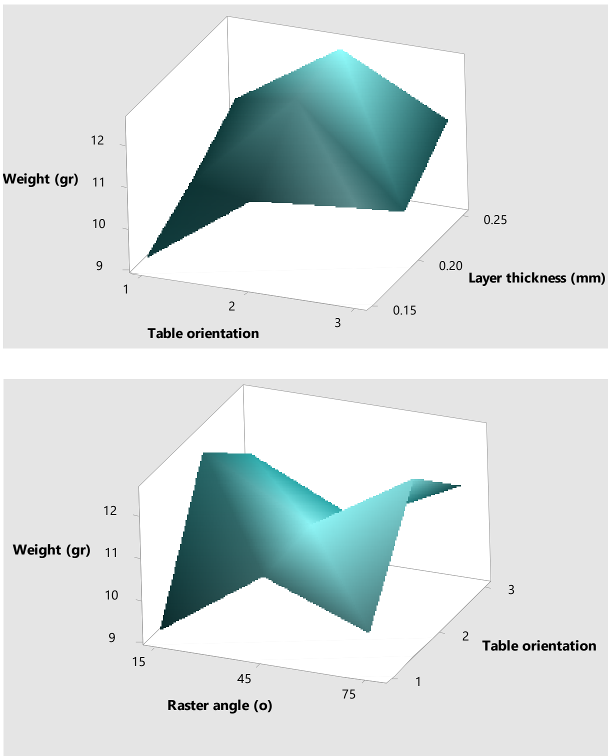

Figure 14. Surface plot of product weight

IV. Conclusions

The main objective of this study is to analyse of the effect of FDM process parameters on the mechanical properties, printing times and costs of products printed with PowerABS filament material using a 3D printer. This study is primarily focused on the effects of the mechanical properties of 3D samples subjected to the influence of three factors; layer thickness, raster angle, table orientation. The results obtained from tests were analysed. As a result, the 3D printing process parameters have significant effects on the mechanical properties (tensile strength, izod impact, and elongation values) and product costs. In addition, it has been observed that optimization has been implemented successfully as a result of the validation experiments. The following results can be drawn from the tests obtained within the limits specified in this study;

- The optimum tensile strength for the 3D printing process parameter was obtained at third level (A_3) of filling structures, at second level (B_2) of raster angle, and at second level (C_2) of table orientation (A_3 B_2 C_2).
- The layer thickness increased the tensile strength values increased proportionally. The 45 degree of raster angle gave the most optimum results.
- The optimum tensile strength of determined for the printing process parameters (table orientation, layer thickness, and raster angle) were 2 (H), 0.25 mm, and 45º, respectively.
- The optimum estimated tensile strength value was found as 13.469 MPa.
- The table orientation of Horizontal (H) gives optimum tensile strength values. It was observed that the table orientation of H gives more strength than other table orientation (F and V). Other table orientations caused the samples more brittle and decrease the elongation of samples.
- The optimum elongation value for the 3D printing process parameter was obtained first level (A_1) of filling structures, at second level (B_2) of raster angle, and at second level (C_2) of table orientation (A_1 B_2 C_2).
- The optimum elongation value of determined for the 3D printing process parameters (table orientation, raster angle, and layer thickness) were 2 (H), 45**º** and 0.15 mm, respectively.
- The optimum estimated elongation value was found as 0.0025 %.
- The 15 and 75 degrees of raster angle made the samples more brittle and elongation (%) of the samples is much reduced.
- The optimum izod impact value for the 3D printing process parameter was obtained at third level (A_3) of layer thickness, at second level (B_2) of raster angle, and at second level (C_2) of table orientation (A_3 B_2 C_2).
- The optimum izod impact value of determined for the 3D printing process parameters (table orientation, layer thickness, and raster angle) were 2 (H), 45º, 0.25 mm, respectively.
- The optimum estimated izod impact value was found as 5.667 kj/m².
- The results of izod impact tests and analysis were shown similarities in results of the tensile strength. As the layer thickness increased, the tensile strength values increased proportionally. The 45 degree of raster angle and table orientation (H) were given the most optimum results of izod impact value. The 15 and 75 degrees of raster angle made the samples more brittle.
- It was observed that the table orientation of H gives more izod impact values than other table orientation (F and V). Other table orientations caused the samples more brittle and decrease the elongation (%) of the samples.
- The optimum printing time for the 3D printing process parameter was obtained at first level (A_1) of layer thickness, at third level (B_3) of raster angle, and at second level (C_2) of table orientation (A_1 B_3 C_2).
- The optimum printing time value of determined for the 3D printing process parameters (layer thickness, table orientation, and raster angle) were 0.15 mm, 2 (H), 75º, respectively

- Optimum estimated printing time value was found as 86.035 min.
- The optimum product weight for the 3D printing process parameter was obtained at third level (A_3) of layer thickness, at third level (B_3) of raster angle, and at second level (C_2) of table orientation (A_3 B_3 C_2).
- The optimum product weight value of determined for the 3D printing process parameters (table orientation, layer thickness, and raster angle) were 2 (H), 0.25 mm, and 75°, respectively.
- Optimum estimated product weight value was founf as 11.622 gr.
- The optimum 3D product printing parameters for the tensile strength, elongation, izod impact, printing time, and product weight were A_3 B_2 C_2, A_1 B_2 C_2, A_3 B_2 C_2, A_1 B_3 C_2, and A_3 B_3 C_2, respectively.
- It was found that the most effective parameter for improving the mechanical properties is as table orientation.
- It can be said that the developed regression model is sufficient and safe for the prediction of mechanical properties due to higher confidence value.
- As observed in the results, by improving the material properties, it will be possible to provide support for mechanical engineers and designers to reduce printing time, filament material use and printing costs.

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