

Optimization of FDM 3D Printer Process Parameters For PETG Material Using TOPSIS Technique

V.V.D. Sahithi¹, N. Srilatha^{2,*}

Abstract

3D printing is a quickly evolving process that builds the desired shape by layering on material. In the era of modern production, additive manufacturing has grown in significance due to its user-friendliness. By using this technique, one can produce complex & intricate geometries with much ease when compared to conventional manufacturing. With the increased demand for 3D printing, consideration towards strength quality and other mechanical properties is also increasing progressively. Optimizing process parameters is crucial for enhancing the mechanical characteristics of items made via additive manufacturing. In this scenario, the primary goal of the current work is to optimize the fused deposition modeling (FDM) 3D printer's process parameters to improve the tensile strength, impact strength, and surface finish of the PETG material manufactured parts. The considered input parameters are raster angles (0° , 15° and 30°) layer thickness (0.1mm, 0.2mm & 0.3mm), and printing temperatures (240°C , 245°C and 250°C). Each input parameter is considered at 3 levels. L_9 array is considered for experimental design. This multi-objective optimization problem is optimized using the TOPSIS optimization approach in order to determine the ideal process parameters.

Keywords: Sustainable development, green material, fracture surface, shear fracture, TOPSIS optimization

INTRODUCTION

In the 1990s, the Fused Filament Fabrication (FDM) technology was first introduced and patented as a moldless way of fabricating three-dimensional solid components[1]. It is an additive manufacturing technique that has revolutionized the field of manufacturing, and it has been slowly substituting the subtractive conventional processes[2]. It gained a lot of importance in the manufacturing industry because of its ability to produce intricate geometries with great precision and accuracy. It is an extremely expensive process at first. The cost of fabricating 3D printers has decreased due to recent advancements in this industry[3]. Consequently, the usage of these printers increased multiple fold. The decreased price of 3D printers has led to their greater use in homes, offices, labs, and many other locations. Because of the usage of multiple materials and easy printing processes, it has progressed over the years to transform the manufacturing process[4]. Numerous industries, including manufacturing, building, jewelry design, custom art and design, architecture, and medical, have used 3D printing. Now

a day's many industries are using 3D printing techniques to produce products, instead of prototype simulations[5]. Optimization of process parameters[6] will help to improve the mechanical properties of the components[7]. Raju et al. optimized the surface roughness by utilizing the Taguchi optimization technique to optimize the infill density, layer thickness, and printing speed[8]. Yadav et al. optimized extrusion temperature and infill density to boost tensile strength[9]. Elkaseer et al. optimized surface inclination angle, layer thickness, printing temperature, speed, and infill

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percentage to dimensional accuracy, the surface roughness of the manufactured item, energy use, and process productivity[10]. Ozen highlighted how the position of failures is affected by the slicer parameters that were used[11]. Ajay et al. tuned the print speed, infill density, and layer height In order to increase tensile, flexural strength, and hardness[12]. Ryan et al. explained the impact of mechanical properties at different loading types[13]. B.H. Lee discussed the effect of air gap, raster angle, and layer thickness on the elastic performance of the ABS prototype[14]. Alafaghani described how process variables affect mechanical qualities, building time, and dimensional accuracy[15]. Akhoundi B explained how the FDM 3D printed specimens' tensile and flexural characteristics were impacted by the filling pattern[16]. Hervan talked about the PLA polymer that is 3D printed and its wear and friction properties[17].Hong conducted tests on 3D-printed textured surfaces.[5]. Keles explained the effect of build orientation on the mechanical reliability of 3D-printed ABS parts. D. Cristian, et al. studied The effects of raster orientation, infill pattern, and infill rate on the mechanical characteristics of 3D-printed objects [18]. R. Anitha examined the crucial factors affecting the prototype quality in fused deposition modeling [19]. Many techniques are used to optimize the parameters using single objective optimization. This research work contributes towards the multi-objective optimization of FDM 3D printer Printing parameters. The main Objectives of the work are to identify the optimum input parameters to increase the tensile strength, reduce the surface roughness, and increase the impact strength of Polyethylene terephthalate glycol (PETG) material using TOPSIS multi-objective optimization technique.

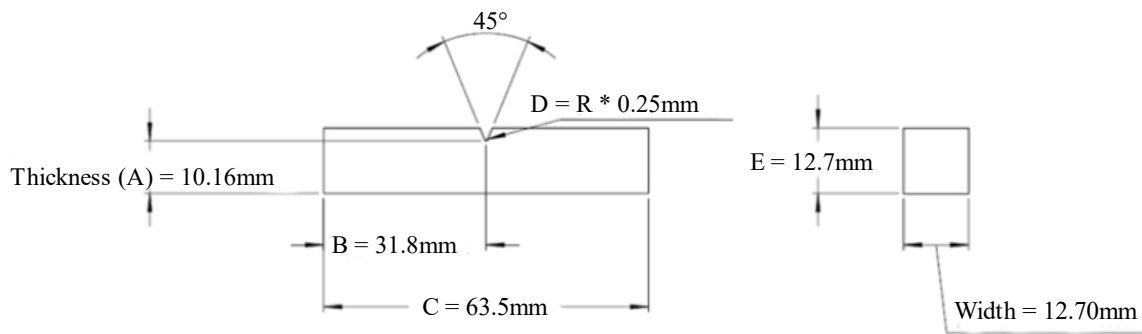
METHODOLOGY

PETG material is used for the test pieces, which were created using CATIA V5 software and an FDM 3D printer[20]. FDM technique is used to print tensile & impact specimens using ASTM standards (ASTM D256, ASTM D638). These test pieces were put through an impact strength test on an IZOD tester, a surface roughness tester to determine the average surface roughness and a tensile strength test on a UTM[21]. The 3D printer used to print all these components is FDM 3D printer AKAR 300Pro. Specifications of the printer are represented in Table1. Tensile and impact strength specimen specifications according to ASTM D256, and ASTM D638 are shown in Figure 1 and Figure 2.

Table 1. Parameters limitation of the 3D printer.

Input parameters	Limits
Infill Density	10-100%
Shell thickness	0.15mm - 2mm
Raster angle	0° - 90°
Diameter to Nozzle	0.05mm - 0.8mm
Print Bed Temperature	30 -70°C
Printing Speed	10mm/s - 70mm/s
Printing Temperature	150-280°C
Layer thickness	0.1mm - 0.4mm
Orientation	0°,45°,90°

In this current study input parameters considered for the study are raster angle, layer thickness and printing temperature. Each input parameter is considered at 3 levels to find out the optimum level for printing. Raster angles are considered at 0°, 15°, and 30° Layer thickness levels are 0.1mm,0.2mm, and 0.3mm & printing temperatures are considered in the range of 240°C, 245 °C,250 °C. So all the 3 parameters each at 3 levels lead to a total of 27 possible interactions. A statistical technique called L9 orthogonal array is used to decrease the number of test cases while assisting testers in analyzing several variables, their interactions, and potential combinations. So using this orthogonal L9 array total of 27 interactions/experiments are reduced to 9. Table 2 shows the L9 experiment design used for the experimentation.



Test specimen dimensions as defined by ASTM D256-10

Figure1. Impact specimen according to ASTM D256.

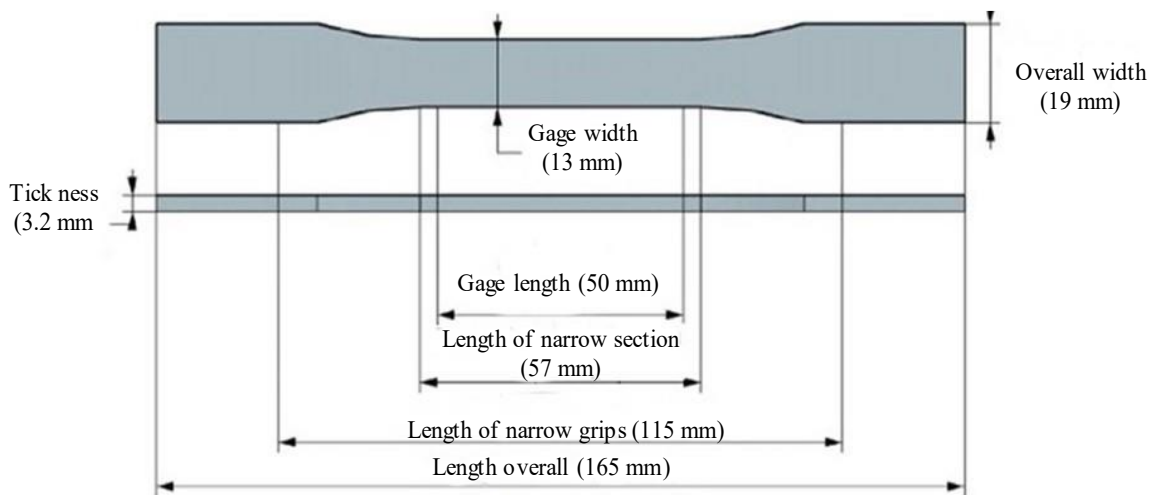


Figure2. Tensile specimen according to ASTM D638.

Table 2. L9 orthogonal array using Taguchi design of experiments.

Experiment number	INPUT PARAMETERS		
	Raster angle	Layer thickness	Printing temperature
E1	0°	0.1mm	240°C
E2	15°	0.1mm	245°C
E3	30°	0.1mm	250°C
E4	0°	0.2mm	245°C
E5	15°	0.2mm	250°C
E6	30°	0.2mm	240°C
E7	0°	0.3mm	250°C
E8	15°	0.3mm	240°C
E9	30°	0.3mm	245°C

After creating an L9 orthogonal array, 9 Tensile, and 9 impact specimens are printed using different levels of raster angles, layer thickness, and printing temperatures with PETG material. 3D-printed tensile and impact specimens are shown in Figure 3 and Figure 4.

These specimens are then put through several tests to determine their surface roughness, impact strength, and tensile strength. All the test results are summarized in Table3.

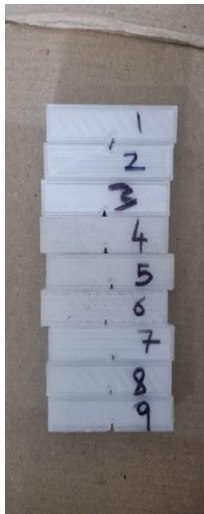


Figure3. 3D-printed PETG material Impact specimens.



Figure4. 3D printed PETG Material Tensile specimens.

Table 3. Experimental results of L9 experiments.

Experiment no.	Tensile test(N/mm ²)	Impact test (joules)	Surface roughness (microns)
E1	20.35	1.5	0.416
E2	20.33	2	0.389
E3	25.48	2.5	0.395
E4	22.02	2	0.58
E5	18.96	1	0.651
E6	22.77	2.5	0.355
E7	17.85	2	0.54
E8	16.37	3	0.589
E9	20.8	2.5	0.834

MULTI-OBJECTIVE OPTIMIZATION

Problems with many objectives are known as multi-objective optimization (MO) problems. Engineering design routinely faces these kinds of issues, and the creation of effective MO algorithms is a vibrant area of study. The output factors that are taken into consideration in this research are surface roughness, impact strength, and tensile strength. Here, choosing the best input parameters such as raster angle, printing temperature, and layer thickness is necessary to achieve high tensile strength, high impact strength, and low surface roughness.

Optimization techniques like Taguchi can optimize the process parameters only when the objective is single. However multiple objectives are involved in the current research problem. So multi-objective optimization techniques are required to optimize the problem that involves multiple objectives. In this work, TOPSIS multi-objective optimization technique is used to efficiently optimize the process parameters in this scenario.

Only when there is a single target may optimization techniques such as Taguchi technique are used. However, the current research challenge involves more than one target. Therefore, to optimize a

problem with many objectives, multi-objective optimization techniques must be used. TOPSIS multi objective optimization technique is used to efficiently optimize the process parameters in this scenario. Seven steps make up the entire TOPSIS process. Table 4 to Table 8 shows the different calculations involved in the TOPSIS process.

Step 1: Make a matrix with M rows (M=number of experiments) and N columns (N=number of output parameters). This matrix is referred as the evaluation matrix.

Table 4. Evaluation matrix of TOPSIS optimization (a_{ij})M ×N.

Experiment number	OUTPUT PARAMETERS		
	Tensile strength(N/mm ²)	Impact strength (joules)	Surface roughness (microns)
E1	20.35	1.5	0.416
E2	20.33	2	0.389
E3	25.48	2.5	0.395
E4	22.02	2	0.58
E5	18.96	1	0.651
E6	22.77	2.5	0.355
E7	17.85	2	0.54
E8	16.37	3	0.589
E9	20.8	2.5	0.834

Step 2: Normalize the evaluation matrix using equation (1). α_{ij} is the normalized evaluation matrix. Here i and j values vary along rows and columns.

$$\alpha_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^M a_{ij}^2}} \quad (1)$$

here $i=0,1,2,3, M$
 $j=0,1,2,3 N$

Table 5. Normalized evaluation matrix.

Experiment no.	Tensile test(N/mm ²)	Impact test (joules)	Surface roughness (microns)
E1	0.350241344	0.236667738	0.226801358
E2	0.349897127	0.315556984	0.212081077
E3	0.438533143	0.394446229	0.215352251
E4	0.378983509	0.315556984	0.316213431
E5	0.326318225	0.157778492	0.354922317
E6	0.391891666	0.394446229	0.193544428
E7	0.307214152	0.315556984	0.294405609
E8	0.281742054	0.473335475	0.321120192
E9	0.357986239	0.394446229	0.454693107

Step3: Compute the weighted normalized decision matrix. It is crucial to remember that every criterion needs to have a distinct weight in order for them to add up to one. Either randomly (not advised) or using expert knowledge (industry standard) can be used to determine the weights.

$$X_{ij} = \alpha_{ij} \times W_j \quad (2)$$

$$\sum_{j=1}^N W_j = 1 \quad (3)$$

W_j in this case stands for the weights of the various output parameters (equation 3). Here, equal weight is assigned to each output parameter. So $W_1=W_2=W_3=0.33$.

Table 6. Weighted normalized decision matrix.

Experiment number	Tensile test(N/mm ²)	Impact test (Joules)	Surface roughness (Microns)
E1	0.116745947	0.078888457	0.075599697
E2	0.116631209	0.105184609	0.070692985
E3	0.146176252	0.131480762	0.071783366
E4	0.126326573	0.105184609	0.105403423
E5	0.108771654	0.052592305	0.118306256
E6	0.130629249	0.131480762	0.064514164
E7	0.102403693	0.105184609	0.098134222
E8	0.093913079	0.157776914	0.107038993
E9	0.119327553	0.131480762	0.151562853

Step 4: For each criterion, identify the best and worst options.

$$X_j^b = Best_{i=1}^M X_i \tag{4}$$

$$X_j^w = Worst_{i=1}^M X_{ij} \tag{5}$$

Table 7. Best and worst value identification

	Tensile test(N/mm ²)	Impact test (joules)	Surface roughness (microns)
X_j^b	0.146176252	0.157776914	0.064514164
X_j^w	0.093913079	0.052592305	0.151562853

Step 5: Determine the target alternative's Euclidean distance from the best/worst alternative. This computes the geometric separation between each metric's value for a specific parameter and its best/worst value across all the parameters.

$$d_i^b = \sqrt{\sum_{j=1}^N (X_{ij} - X_j^b)^2} \tag{6}$$

$$d_i^w = \sqrt{\sum_{j=1}^N (X_{ij} - X_j^w)^2} \tag{7}$$

Step6: Determine how similar each option is to the least favorable option. Our TOPSIS scores are the outcomes.

$$S_i = \frac{d_i^b}{d_i^b + d_i^w} \tag{8}$$

Step7: Rank the alternatives according to the S_i values.

RESULTS AND DISCUSSIONS

Using an FDM 3D printer and a variety of process parameters, including raster angle, layer thickness, and printing temperature, the test pieces were created from PETG material. Tensile strength, impact strength, and surface roughness are assessed on each specimen. In order to reduce surface roughness and maximize impact and tensile strength, process parameters were identified by TOPSIS multiple objective optimization techniques. From the results shown in Table 3 maximum tensile strength is attained for the third specimen at 30° raster angle, 0.1mm layer thickness, and 250° C printing temperature. Surface roughness is optimum for specimen 2 at 15° raster angle, 0.1mm layer thickness,

and 245° C printing temperature. Impact strength is optimum for 3rd, 6th, and 9th specimens. Each mechanical property is optimum at different input parameter conditions. So, to optimize these multiple objectives TOPSIS optimization technique is applied, and the experiments are ranked according to the S_i value calculations as shown in Table 9.

Table 8. Ranking TOPSIS scores.

	d_i^b	d_i^w	S_i	Rank
E1	0.084926	0.083566	0.495963	7
E2	0.060639	0.099106	0.620403	5
E3	0.027282	0.123772	0.819387	1
E4	0.069512	0.077119	0.525939	2
E5	0.123921	0.036425	0.227164	9
E6	0.030548	0.123081	0.801156	3
E7	0.076238	0.07545	0.4974	6
E8	0.067378	0.11422	0.628971	4
E9	0.094815	0.082881	0.466422	8

Table 9. Ranking the experiments using TOPSIS analysis.

Experiment no.	Tensile test(N/mm ²)	Impact test (joules)	Surface roughness microns)	Rank
E1	20.35	1.5	0.416	7
E2	20.33	2	0.389	5
E3	25.48	2.5	0.395	1
E4	22.02	2	0.58	2
E5	18.96	1	0.651	9
E6	22.77	2.5	0.355	3
E7	17.85	2	0.54	6
E8	16.37	3	0.589	4
E9	20.8	2.5	0.834	8

Layer thickness has its significant impact on the mechanical properties of the PETG material. The tensile strength of the specimens are giving good results at 0.1 and 0.2mm but the tensile strength is very poor at the higher layer thickness value (0.3mm). Raster angle has higher impact on the impact strength. Specimens with higher raster angle(30°) has higher impact strength irrespective of other parameters. Combined effect of these parameters is more significant in the case of surface roughness. Even though different parameters are having different impact on different mechanical properties. To get the maximum benefit the results it is decided that 30° raster angle, 0.1mm layer thickness and 250° C printing temperature are optimum parameters to achieve the best mechanical properties.

CONCLUSIONS

This work used FDM technology along with three different processing parameters (layer thickness, raster angles and printing temperatures) to 3D print PETG thermoplastic material.

The tensile strength, impact strength and the surface roughness for the printed specimens have been investigated. From the results it is clearly seen that less layer thickness has a good impact on the tensile strength. High raster angles are desirable to achieve maximum impact strength. To find out the optimum input parameters in this multi objective scenario TOPSIS optimization method was applied. Based on the obtained results and TOPSIS calculations all 9 experiments are ranked according to their preferential order. The best mechanical properties are achieved by selecting the input parameters that match to the top-ranked alternatives. According to the multi-objective optimization calculations Raster angle 30°, Layer thickness of 0.1mm, and Printing temperature of 250°C are decided as the best process parameters to achieve the optimum tensile strength, impact strength, and surface roughness.

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