International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 07 Issue: 06 | June - 2023 SJIF Rating: 8.176 ISSN: 2582-3930

Effect of Process Parameters on Tensile Strength of Polyethylene Terephthalate Glycol Material Specimens 3D Printed Using Material Extrusion

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Abstract - Material extrusion (ME) or Fused deposition modeling (FDM) is one of the additive manufacturing methods in which the thermoplastic material is heated to the extrusion temperature and then extruded by the nozzle to add layer upon layer to prepare a three-dimensional part. The quality and mechanical properties of the material extruded 3D printed part depends on the selection of process parameter and material used to print any part. So, in the present study, the effect of an individual process parameter such as infill pattern, extrusion temperature and raster angle on the tensile strength of polyethylene terephthalate glycol (PETG) material is observed. It is a thermoplastic material with low cost and higher strength than other polymers. Tensile specimens are 3D printed as per the ASTM standard D638 with different combinations of parameters using the design of experiments and tested using a universal testing machine (UTM). As the outcome of this study, it is observed that the tensile strength increases with an increase in all the selected process parameters. Further, the rectilinear pattern, 240 ^{0}C extrusion temperature and 0/+45^0 raster angle is found to be the optimal set of parameter while the extrusion temperature is obtained as the most influencing parameter using Analysis of Variance (ANOVA).

Key Words: analysis of variance, fused deposition modeling, polyethylene terephthalate glycol, process parameters, tensile strength.

1.INTRODUCTION

Additive manufacturing (AM) is one of the manufacturing technologies of industry 4.0 that is used to manufacture three-dimensional prototypes directly from computer-aided design (CAD) models.[1] In AM, the printing of any part is done by adding layer after layer without removing the material like in traditional manufacturing methods.[2] As the part quality and properties of an additively manufactured part depend upon different process parameters, its use is still limited.[3] It is suitable for complex structures and it can print multi-materials easily. This technology consists of various processes that are cost-effective and it has lesser build time along with higher flexibility.[4]

Material extrusion (ME) also called fused deposition modeling (FDM) is the AM method that is widely used to prepare 3D-printed parts of thermoplastics or composites.[5] FDM also adds layers upon layers to create a part like any other AM method. Material is added as per the slicing of the part, which means waste of the material and cost are reduced. Despite these advantages, 3D-printed parts using FDM has some deficiencies in part quality and strength of the part. So, the use of FDM in end-use products is still limited. Therefore, the selection of process parameters and materials is becoming more important at the fabrication stage. The selection of process parameters depends upon the material selected to prepare a part. Different process parameters are classified according to the physical characteristics, orientations in which part is being printed, material being deposited, etc. FDM is commercially available to the market in the 1990s after being patented by Stratasys in 1989. The FDM is working on the principle of fusing the layers of the parts together before it is solidified. Figure 1.1 shows the schematic of fused deposition modeling. In FDM, thermoplastic material in form of filament is heated to extrusion temperature and then deposited on the print bed to create any 3D part.[6] The filament is transferred to the extruder by filament-driven pulleys. The nozzle is used to add layers to the print bed and it is moved according to the G-codes generated by the CAD model. The semi-liquid material deposited on the bed is then cooled down at room temperature. The support material is used or parts can be prepared using multi-materials to prepare any complicated parts. Different thermoplastic materials used in FDM are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), polyethylene terephthalate glycol (PETG), polyether ether ketone (PEEK), nylon, etc. FDM is not only limited to the polymers but also composites are used to strengthen the part.

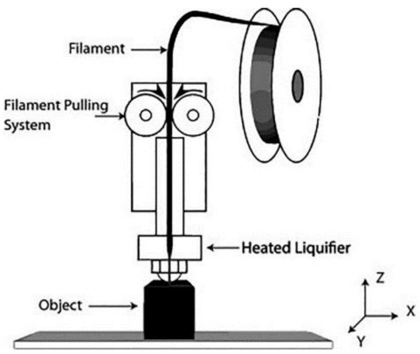

Fig. 1.1 Schematic of Fused deposition modelling [1]

Srinivasan et al.[4] investigated the effect of infill density on tensile strength and surface roughness of PETG parts. According to this study, parts have a higher tensile strength at high infill density whereas lower surface roughness at higher infill density. Also, layer thickness has more influence on tensile strength. Srinivasan et al.[7] conducted another study to find the impact of the infill pattern on the strength of the part printed of PETG material. It was found that the grid pattern followed by honeycomb and rectilinear pattern has more impact on the tensile strength of the part as tensile strength was higher for these patterns. It is because the grid pattern provides strong bonds in printed parts. The honeycomb infill pattern has more tendency to hold its intermolecular layers. The highest tensile strength was obtained for the grid pattern while the lowest tensile strength was obtained in the concentric infill pattern. According to another study by Srinivasan et al.[1], infill density and layer thickness are directly and indirectly proportional to the tensile strength respectively. The infill pattern with build orientation produces variations in tensile strength. Higher tensile strength values were recorded for grid pattern, 0.1 mm layer thickness and infill density of 80%. With the increase in infill density, the surface roughness value decreases and for increased layer thickness, the surface roughness value increases.

Durgashyam et al.[8] Concluded in their study that the layer thickness has more impact on both tensile and flexural strength of the part than feed rate and infill density. Tensile strength increases at lesser layer thickness and feed rate with higher infill density. Good flexural strength was observed at minimum layer thickness, moderate feed rate, and low infill density. According to the study by Panneerselvam et al.[9], the hexagonal pattern has a greater influence on the tensile strength of the material. High shore-D hardness was measured at higher infill percentage, hexagonal pattern, and higher-layer height. The infill pattern was found to have a greater influence on the tensile strength of PETG parts. Hanon et al.[10] studied an anisotropy evaluation of different raster angles, print orientations, and infill percentages by taking PETG as a build material. As per the study raster direction as well as orientation parameters have a considerable impact on the tensile strength and also on the elongation values of the printed parts.

Yadav et al.[11] investigated the process parameters using an adaptive-network-based fuzzy inference system (ANFIS) by taking PETG, ABS, and multi-material (60% ABS and 40% PETG). The process parameters selected were extrusion temperature, layer height, and material density. It was found that tensile strength is more affected by extrusion temperature rather than layer height. Higher tensile strength was noted at the higher extrusion temperature up to a certain limit. A minimal error percentage was observed by created ANFIS model. Barrios et al.[12] concluded in their study of reducing surface roughness that the flow rate and the print acceleration were the parameters with greater influence than the remaining considered parameters. The section of the deposited filament is somewhat circular due to the flow rate. Print acceleration was responsible for keeping the section more or less uniform with respect to printing load.

2. MATERIALS AND METHODS

2.1 Selection of Material

In this work, Polyethylene Terephthalate Glycol (PETG) is selected as a build material because of its numerous advantages and applications. PETG's benefits include being durable and affordable, food-safe and recyclable, easily formable and colorable, and emitting no toxic or unpleasant odours. Also, it is not brittle before printing that is in filament form. It is more flexible than other polymer materials used in FDM such as ABS, PLA, etc.[9] PETG is used in a variety of products, including food and beverage containers, machine guards, retail stands and displays, medical and pharmaceutical applications, and 3D printing. The following specifications apply to the filament: 2.85 mm in diameter, 1.27 g/cm^3 in density, 230 to 250 ºC for extrusion, and 60 to 70 ºC for the bed.

2.2 Selection of Process Parameter

As infill pattern and extrusion temperature directly relate to the strength and raster angle is still an unexplored parameter to improve print time. So, infill pattern, extrusion temperature and raster angle are selected as varying process parameters. Layer thickness of 0.2 mm and nozzle diameter of 0.4 mm are taken into consideration as a constant process parameter.

Infill pattern is the internal structure of the part that holds the material deposited to prepare any part. For this study, three infill patterns are selected i.e., grid, honeycomb and rectilinear pattern.

These infill patterns are selected as these pattern gives enhanced results. Extrusion temperature is one of the most influencing parameters as the material properties will give different values of properties at different temperatures. Three levels of the extrusion temperature were selected in this study such as 230 ^{0}C with a successful interval of 5 ^{0}C. Raster angle is yet an unexplored process parameter that can have successful participation to enhance the mechanical properties of the thermoplastic material used for printing. In this study, 0^0, 0/+45^0 and +45/-45^0 are selected as levels of raster angle.

2.3 3D Printing of Specimens

To investigate the mechanical properties of PETG material, specimens are prepared and then undergo tensile testing. For that, the specimens were prepared according to the ASTM standard D638 Type-IV in Fusion 360 as shown in Figure 2.1. The specimen has length of 115 mm, width of 19 mm and thickness of 3.2 mm. Then the specimens were 3D printed using Ultimaker 2 extended + 3D printer as per Figure 2.2. Before going for actual printing, .stl file generated of CAD model is repaired in Autodesk Netfabb to rectify any errors present in .stl file of tensile specimen and then repaired specimen is exported as new .stl file as per Figure 2.3. All the specimens were prepared using Taguchi L9 orthogonal array, therefore the levels of selected process parameters and constant parameters were set in Simplify 3D. Total of 18 specimens were prepared, two of each experiment for repeatability purpose.

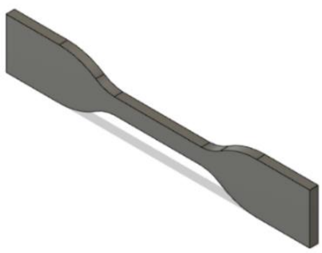

Fig. 2.1 CAD model of tensile specimen

Fig. 2.2 Ultimaker 2 Extended +

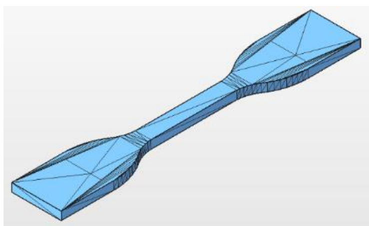

Fig. 2.3 Repaired .stl file

2.4 Tensile Testing

Testing of tensile specimens is done using UTM DTRX having a maximum load capacity of 10kN. The specimen is fitted into the tensile jaws and checked for alignment. All the

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specimens tested were prepared using ASTM standard D638 Type – IV. Specimens were tested at the speed of 50 mm/min. Total of 18 (two of each experiment) specimens were tested to find the average tensile strength of 3D printed PETG specimens. Figure 2.4 indicates the UTM setup. The values of DOE and experimental results are tabulated in Table 2.1 whereas Figure 2.5 depicts the tested specimens.

Fig. 2.4 UTM setup

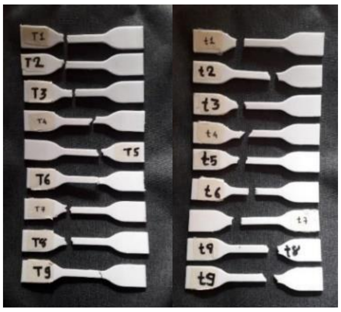

Fig. 2.5 Specimens after Tensile testing

3. RESULTS AND DISCUSSION

3.1 Main Effect Plot for Means

Table 3.1 shows the results obtained by experiments and predicted values of average tensile strength obtained using the regression equation. Minitab software is used to analyze the results and to the get optimum set of parameters. Figure 3.1 shows the main effect plot for the means of each variable process parameter i.e., infill pattern, extrusion temperature and raster angle with three levels of each for the tensile strength of PETG. It is found from the main effect plot for means that the raster angle has not much effect on average tensile strength. Increasing the raster angle from the first to the third level leads to an increase in average tensile strength. The infill pattern has more effect than the raster angle on average tensile strength. Average tensile strength is increasing with increasing the levels of infill pattern. Average tensile strength is most affected by extrusion temperature. It is found that the average tensile strength is increasing with an increase in extrusion temperature. However, the increasing trend is not the same throughout as it is suddenly increasing between 230 ^{0}C and 235 ^{0}C, while slightly increasing from 235 ^{0}C to 240 ^{0}C. Also, it is observed from the main effect plot that rectilinear pattern, 240 ^{0}C extrusion temperature and 0/+45^0 raster angle has the highest mean values while grid pattern, 230 ^{0}C and +45/-45^0 raster angle have the lowest mean values. The maximum and minimum value of the average tensile strength of each varying parameter is shown in Table 3.2.

Table 3.1 Experimental and predicted values of Average tensile strength

Specimen	Average tensile strength	S/N ratio	Average predicted tensile strength	Error
1	10.484	20.4105	10.647	1.55
2	12.033	21.6075	11.881	1.26
3	12.863	22.1868	12.719	1.12
4	11.242	21.0169	11.22	0.20
5	12.661	22.0494	12.058	4.76
6	12.436	21.8936	13.292	6.88
7	10.694	20.5828	11.397	6.57
8	13.597	22.6689	12.631	7.10
9	13.734	22.7559	13.865	0.95
Average Error				3.38

Table 3.2 Response table for Means of Average tensile strength

Level	Infill pattern	Extrusion temperature	Raster angle
1	11.79	10.81	12.07
2	12.11	12.76	12.17
3	**12.67**	**13.01**	**12.34**
Delta	0.88	2.20	0.26
Rank	2	1	3

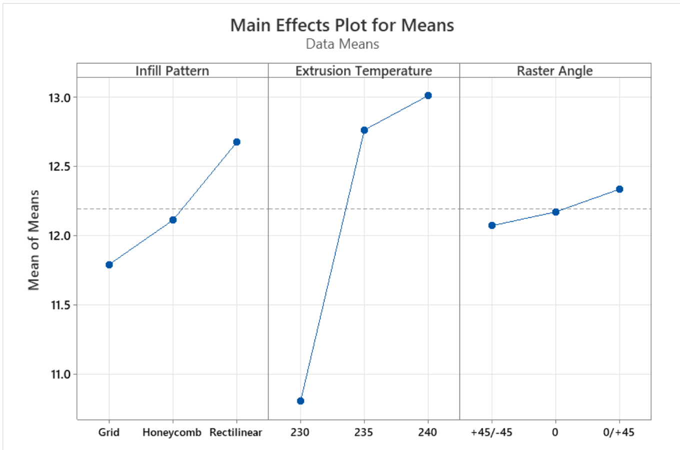

Fig. 3.1 Main effects plot for Means of Average tensile strength

3.2 S/N Ratio

Figure 3.2 shows the main effect plot for S/N ratios of average tensile strength. It consists of the selected varying process parameters required to maximize the S/N ratios of average tensile strength. It is observed from the plot for S/N ratios that average tensile strength shows an increasing trend with increasing levels of process parameters. Table 3.3 shows the means S/N ratios at each level of all three process parameters. To determine the S/N ratios, a larger is better type response is used to optimize the results. It is found that the average tensile strength has an increasing trend with an increase in the levels of all three factors. The extrusion temperature plays a major role in obtaining the higher value of average tensile strength. It is concluded from the response table for S/N ratios that the optimal set of process parameters for maximum tensile strength is P_3-T_3-A_3.

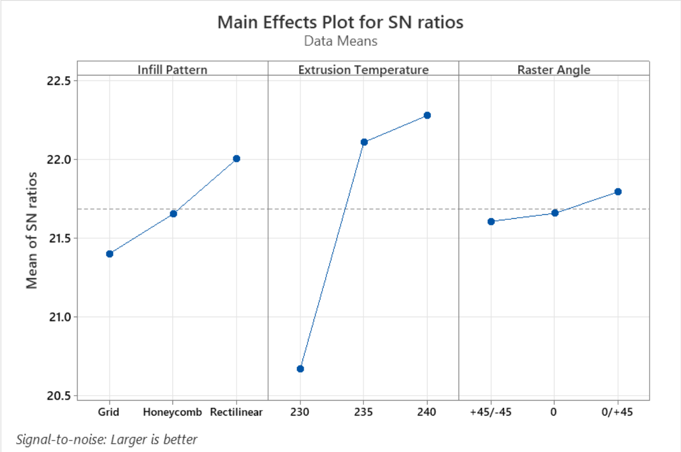

Fig. 3.2 Main effects plot for S/N ratios of Average tensile strength

Table 3.3 Response table for S/N ratios of Average tensile strength

Larger is Better

Level	Infill pattern	Extrusion temperature	Raster angle
1	21.40	20.67	21.61
2	21.65	22.11	21.66
3	**22.00**	**22.28**	**21.79**
Delta	0.60	1.61	0.19
Rank	2	1	3

3.3 Regression Analysis

The regression equation of average tensile strength (Equation 1) is mentioned below and it is used to calculate predictive values of average tensile strength for all the specimens at selected varying process parameters.

$$\text{Average tensile strength (MPa)} = 8.84 + 0.441 * \text{Infill pattern} + 1.102 * \text{Extrusion temperature} + 0.132 * \text{Raster angle} \quad (1)$$

Table 3.4 shows the model summary of average tensile strength which includes R-sq (Coefficient of determination), adjusted R-sq and predicted R-sq.

Table 3.4 Model summary of Average tensile strength

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
0.722722	76.62%	62.59%	7.59422	32.02%	44.41	25.39

3.4 Contour Plot

Figure 3.3 shows contour plots of average tensile strength and two factors to examine the relation between them. From Figure 3.3 (a), it was found that a high level of infill pattern and high level of extrusion temperature leads to a higher value of average tensile strength. Figure 3.3 (b) shows that high values of infill pattern and raster angle give a higher value of average tensile strength. Also, from Figure 3.3 (c), it was observed that higher average tensile strength is obtained at the high levels of extrusion temperature and raster angle.

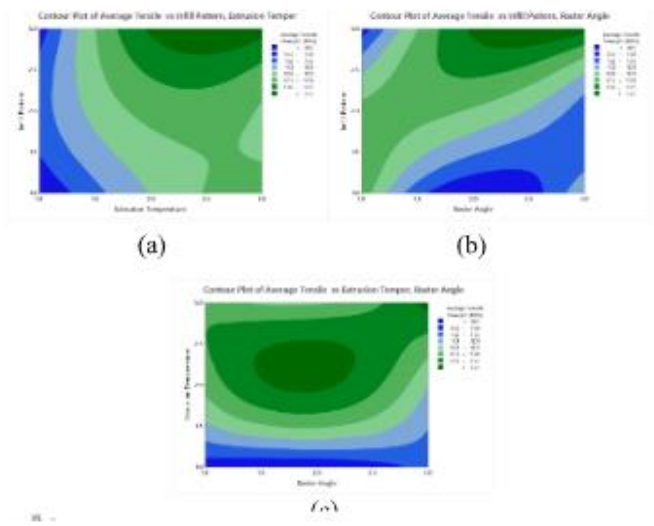

Fig. 3.3 Contour plots of Average tensile strength vs Process parameters

3.5 Analysis of Variance

Table 3.5 shows the ANOVA results which is consisting of the contribution of each factor, f-value, p-value (calculated probability), etc. The factors are considered as significant if their p-value is less than the α-value which is 0.05. It is found from the ANOVA table that the extrusion temperature is a significant factor as its p-value is less than the α-value. Infill pattern and raster angle are not considered significant factors as their respective p-values are greater than the α-value. The model is considered as significant as its p-value is 0.049 which is less than the α-value. Extrusion temperature has contributed more than infill pattern and raster angle which is 65.25% of the total.

Table 3.5 ANOVA of Average tensile strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	8.5589	76.62%	8.5589	2.8530	5.46	0.049
Infill Pattern	1	1.1660	10.44%	1.1660	1.1660	2.23	0.195
Extrusion Temperature	1	7.2886	65.25%	7.2886	7.2886	13.95	0.013
Raster Angle	1	0.1043	0.93%	0.1043	0.1043	0.20	0.674
Error	5	2.61	23.38%	2.61	0.52		

		16		16	23		
Total	8	11.1705	100.00%				

3.6 Predicted Value

The predicted values of average tensile strength are calculated using a regression equation which are tabulated in Table 3.1. After comparing the experimental results and predicted values of average tensile strength, it is observed that the average error is 3.38% which is not so considerable. So, the regression equation is found significant.

3.7 Influence of Process Parameters on Average Tensile Strength

As the process parameters have their effect on the response variable, the effect of infill pattern, extrusion temperature and raster angle are plotted in the bar chart shown in Figure 3.4. As per the bar chart, the rectilinear pattern along with 240 ^{0}C extrusion temperature and raster angle of 0/+45^0 leads to the maximum value of average tensile strength. The set of parameters that gives the lowest value of average tensile strength is a grid pattern, 230 ^{0}C and 0^0 raster angle.

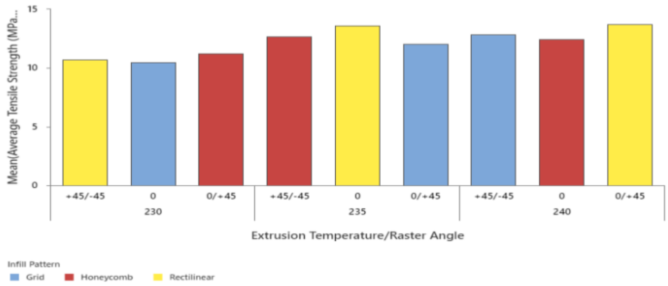

Fig. 3.4 Bar chart of mean for Average tensile strength

4. VALIDATION OF RESULT

An optimum set of process parameters is obtained through Taguchi analysis. It is validated using a regression equation. Table 4.1 shows results obtained by Taguchi analysis, regression equation and error between them. Results obtained from Taguchi analysis and regression equation are close to similar with a minor error. So, it is validating the set of optimum parameters obtained.

Table 4.1 Validation of response variables

Optimum combination	**P**	**T**	**A**	**Result**			
				Response variable	Taguchi analysis	Regression equation	Error
P_3-T_3-A_3	Rectilinear	240	0/+45	Average tensile strength	13.6348	13.865	0.2302

5. CONCLUSIONS

The effect of infill pattern, extrusion temperature and raster angle on tensile specimens of PETG material 3D printed using FDM have been carried out in this study. It is found from the study that, maximum average tensile strength is achieved at the higher levels of infill pattern, extrusion temperature and raster angle. As per ANOVA, the extrusion temperature is significant as its p-value is less than 0.05 and the model is also proved to be significant as its value is less than the p-value. Extrusion temperature has a 65.25% of contribution to the model. Contour plots give the relation between two parameters which also proves that at higher levels of parameters the average tensile strength increases. It is observed that the average error between the predicted value obtained using the regression equation and experimental results is 3.38% which is considerable and suggests that the regression equation is significant to obtained predicted values of a different set of parameters.

Present work can be extended for further research in this area by changing process parameters like infill density, raster gap, contour width, etc. The effect of the process parameters selected in this study can be investigated further by changing response variables such as compressive strength etc. Also, this study can be extended by using composited with PETG material to enhance the properties.

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