Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

Development of Thermoplastic Feedstock Filament for 3D Printing

Praveen Jeyachandran[1*], Balu Patil[1], Mrityunjay Doddamani[1], Srikanth Bontha[1] and Vamsi Krishna Balla[2]

[1]Advanced Manufacturing Laboratory, Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal - 575025, India.

[2] Bioceramics and Coating Division, CSIR-Central Glass and Ceramic Research Institute, Kolkata – 700032, India.

Abstract

3D Printing is an Additive Manufacturing (AM) technique which employs layer by layer building process to produce an end product. Such AM processes help in manufacturing parts with reduced cycle time and zero tooling cost. The utility of 3D Printing is restricted as compared to traditional manufacturing techniques owing to limited material options. This article in 3D Printing with focus on thermoplastics aims at increasing material option. The feedstock for the current study is developed using extrusion process. Pilot study is conducted to estimate the effect of extrusion process parameters (barrel and die temperature, screw and take off speed) on filament diameter variation, tensile strength and tensile modulus. Tensile test is conducted on extruded filament as per ASTM D638. Response surface plots are presented to understand the influence of process parameters. Mathematical model is formulated based on response surface methodology to predict the output responses.

Keywords: 3D Printing, Feedstock Filament, thermoplastics, Response Surface Methodology.

1. INTRODUCTION

3D Printing (3DP) process is an layered construction of physical objects using Additive Manufacturing (AM) Technology. CAD file of the physical object irrespective of geometric complexity is given as input to the system, which slices the object into number of layers and generate tool path for each layer to print the given object. Despite the advantages likes tool-less manufacturing, reduced manufacturing time, reduced material wastage, the use of 3DP is limited because of available material choices and proprietary machines.

Sood A.K. et al. [1] studied mechanical properties of 3D printed Acrylonitrile Butadiene Styrene (ABS) parts. Wear properties of the parts printed using ABS-Iron and ABS-Copper composite filament are studied by Kamaljit Singh et al [2]. Unidirectionally 3D printed Polylactic acid (PLA) components are tested for mechanical responses by Song Y. et al. [3] Omar Ahmed Mohamed et al. [4] performed Dynamic Mechanical Analysis on 3D Printed PC-ABS composite parts. Miquel Domingo-Espin et al. [5] did anisotropic study and finite element modelling of 3D printed Poly Carbonate (PC) parts for structural applications. Layer by layer printed ULTEM® parts are tested for its mechanical and thermal property by Zaldivar R.J. et al. [6]. Composite filament of Nylon and aluminium oxide (N-Al_2O_3) is used by Singh R. et al. [7] to study wear properties.

The feedstock materials widely used in 3DP in filament form are ABS, PC, PC-ABS, Nylon, Nylon – Aluminium oxide, ULTEM® and PLA [8, 9]. From the current scenario it is evident that the 3D Printing has limited material options to manufacture structural and functional end products. To overcome the limited material options, this study aims at developing thermoplastic feedstock material in filament form using HDPE. HDPE is proven to be suitable for structural and functional applications [10, 11]. The filament for the HDPE feedstock material is extruded using single screw extrusion process.

The melt quality of the extrusion is found to be influenced by the screw geometry, barrel temperature, die temperature and extrusion pressure [12]. Singh R et al. [13] observed that barrel and die temperature, take-up speed plays a vital role in obtaining filament of desired quality. Screw geometry, temperature of heating zones and viscosity of the polymer also has significant effect on the extrusion process as reported by Sorroche J.V. et al. [14].

Present work attempts to develop HDPE thermoplastic feedstock filament using single screw extrusion process. Designs of experiments are performed based on Taguchi's L9 Orthogonal Array (OA) for barrel and die temperature with varying screw speed. Filament is extruded to have minimum diameter variation. Mathematical model is proposed based on Response Surface Methodolgy (RSM) to analyse the effects of different process parameters on tensile strength (TS) and modulus (TM). Response Surface plots are also presented for clarity.

2. MATERIALS AND METHODS

HDPE thermoplastic in granular form is used as feed material. Single Screw Extruder is utilised to extrude HDPE filament. The influencing parameters considered are barrel temperature, screw speed, die temperature, take-off speed, die diameter, water-bath temperature. The die of 3 mm diameter is used to extrude filament in a controlled manner. The temperature of the water bath is maintained at room temperature by external cooling system. So the variable parameters considered are barrel temperature, die temperature and screw speed.

Tensile test on the filaments are done as per ASTM D638 [2] using Tinius Olsen H75kS UTM machine at the strain rate of 50 mm/min. Three samples of required dimensions are cut from different portions of the extruded filament lot.

Table 1: Process parameters and their levels for extrusion

Parameters	Levels		
	1	2	3
Barrel Temperature (A), °C	130	150	170
Screw Speed (B), rpm	25	30	35
Die Temperature (C), °C	125	145	165

*Praveen Jeyachandran, Email: praveen.rjc92@gmail.com

ISBN: 978-93-80689-28-9

Table 2: Orthogonal Array, Output Responses and S/N ratios

Experiment Run	Barrel Temperature (ºC)	Screw Speed (rpm)	Die Temperature (ºC)	Tensile strength (TS)		Tensile Modulus (TM)	
				Mean (MPa)	S/N ratio	Mean (MPa)	S/N ratio
1	130	25	125	17.10±0.40	24.6599	498.75±02.93	53.9577
2	130	30	145	16.90±0.14	24.5577	457.30±05.09	53.2040
3	130	35	165	16.36±0.35	24.2757	512.53±02.50	54.1944
4	150	25	145	16.60±0.56	24.4022	533.40±00.28	54.5411
5	150	30	165	16.00±1.27	24.0824	505.65±03.46	54.0770
6	150	35	125	15.70±0.81	23.9180	462.93±30.46	53.3103
7	170	25	165	16.40±0.56	24.2969	521.25±11.51	54.3409
8	170	30	125	15.90±1.20	24.0279	451.71±37.40	53.0972
9	170	35	145	16.50±0.00	24.3497	485.20±06.52	53.7184

3. EXPERIMENTAL DETAILS

3.1 Design of Experiments

Barrel temperature, screw temperature and die temperature are considered critical in obtaining the filament of required diameter. The working range of these parameters is found out from trial and error method, previous experience and industrial experts. The levels of the parameters are listed in Table 1. In case of full factorial approach, numbers of experiments required are high. Design of experiments (DOE) is formulated based on Taguchi's L9 Orthogonal Array (Table 2) which gives a well-balanced minimum number of experiments sufficient enough to optimize the screw extruder [15]. Using Signal to Noise ratios (S/N), the optimum results are predicted.

3.2 Extrusion

Using the formulated L9 array, the filament is extruded using the single screw extruder. For the given set of temperature conditions, the ratio between screw speed and take-off speed has to be in a certain ratio to extrude the filament of desired diameter [12]. Thereby take-off speed is adjusted to extrude the filament of desired diameter so that it will qualify as feedstock filament for 3DP. The temperature of the water bath is maintained at room temperature (28ºC) to ensure the uniformity of the extruded filament. The diameter of the extruded filament is measured for diameter variations and the variations are found to be minimum. The mean values of tensile strength and tensile modulus of the filaments are listed in Table 2.

4.1 RESULTS AND DISCUSSION

4.2 Analysis of Variance (ANOVA)

Statistical validation of the results is done by ANOVA. MINITAB 17 software is used for the purpose. ANOVA is performed for both TS and TM to find the most influencing parameters at 80% probability level. From Table 3 it is found that barrel temperature and screw speed are most influencing for tensile strength and screw speed and die temperature are found most influencing for tensile modulus. The physics behind these observations are explained as follows: The crystallinity of extruded filament determines the strength and modulus [16]. The degree of crystallization will be higher when the barrel temperature is kept closer to crystallisation point and it decreases as the barrel temperature increases. Degree of crystallization is also affected by resident time of the melt inside the barrel. Higher resident time signifies slower screw speed which results in higher degree of crystallisation than the higher screw speed which has low resident time [12, 17].

4.3 S/N Ratios

The sensitivity of quality characteristics from desired value is measured by S/N ratio. Whereas signal highlights the effect on average response and the noise represents the deviations from output [15]. The criterion, "larger is better" is used in this work (equation (1))

Larger is better (maximize):

$$S/N = \quad -10log[\frac{1}{n}\sum\left(\frac{1}{Y^2}\right)] \tag{1}$$

where 'Y' is the output response (tensile strength and tensile modulus) and n is the number of observations (n= 3).

Non-linearity effect is observed (Fig. 1) for both tensile modulus and strength. The objective here is to obtain maximum tensile strength and modulus. Hence the optimum levels contributing to maximum tensile strength and modulus are tabulated as in Table 4.

4.4 Mathematical Model

Mathematical model is developed for both TS and TM based on Response Surface Methodology (RSM) using MINITAB 17 software. The derived full quadratic equation for tensile strength and tensile modulus are as mentioned as equations (2) and (3) respectively.

Table 3: Analysis of Variance (ANOVA) for Tensile Strength (TS) and Tensile Modulus (TM)

Source	DF	Tensile Strength (TS)				Tensile Modulus (TM)			
		Adj SS	Adj MS	F-Value	Contribution (%)	Adj SS	Adj MS	F-Value	Contribution (%)
A	2	0.7697	0.38484	7.47	48.53	349.4	174.7	0.57	5.53
B	2	0.4577	0.22884	4.44	28.84	3329.5	1664.7	5.41	52.57
C	2	0.3900	0.17951	3.48	22.26	2647.7	1323.9	4.31	41.88
Error	2	0.1030	0.05151			614.9	307.5		
Total	8	1.6894				6941.5			

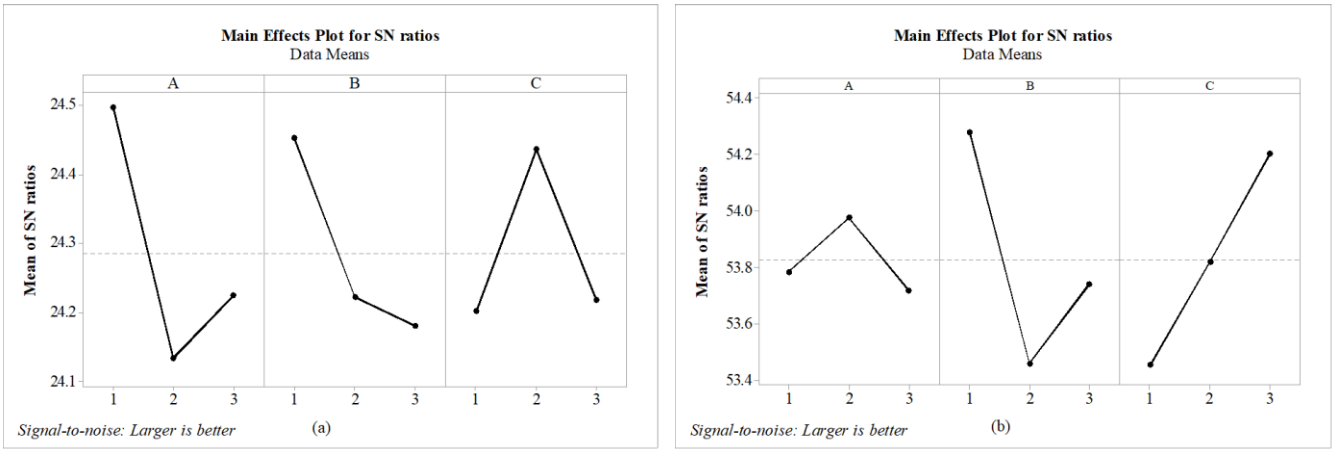

Fig. 1. Main effect plot for S/N ratios (a) Tensile Strength (b) Tensile Modulus

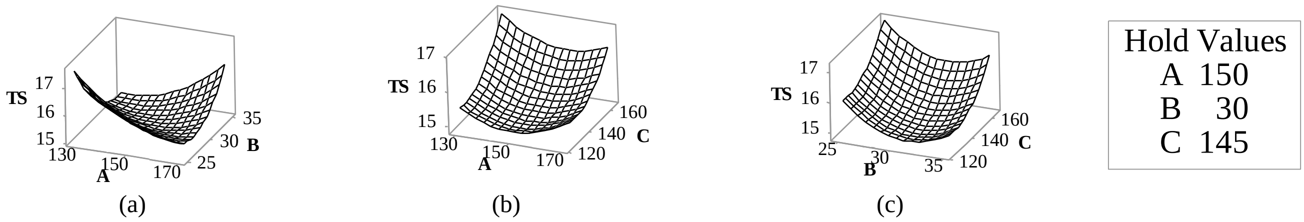

Fig. 2. Response Surface Plot for Tensile Strength (TS) vs (a) Barrel Temperature, Die temperature. (b) Barrel Temperature, screw speed. (c) Die Temperature, Screw speed.

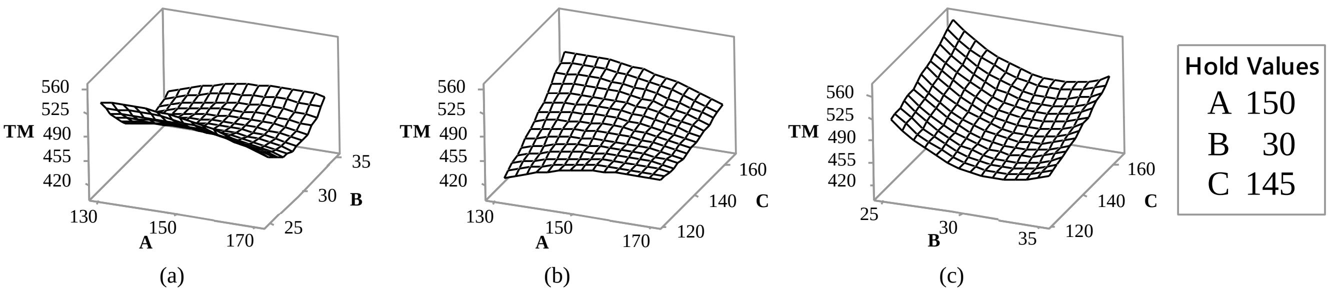

Fig. 3. Response Surface Plot for Tensile Modulus (TM) vs (a) Barrel Temperature, Die temperature. (b) Barrel Temperature, screw speed. (c) Die Temperature, Screw speed.

$$TS = 122.7-0.5924\times A-3.073\times B-0.2487\times C+0.001187\, A\times A+0.02713\, B\times B+0.001129\, C\times C \quad (2)$$

$$TM = 1276+11.54\times A-125.4\times B+2.534\times C-0.03218\, A\times A+1.606\, B\times B+0.02047\, C\times C+0.1604\, A\times B \quad (3)$$

The error between the experimental and predicted values lie below 1%, which shows the developed mathematical models can be used for prediction of Tensile Strength and Tensile Modulus.

4.5 Response Surface Plot

Using the Equations (1) and (2), response surface plots are drawn to find the influence of process parameters on Tensile Strength and Tensile Modulus respectively. Fig. 2 shows the influence of process parameters namely barrel temperature, die temperature and screw speed on tensile strength. From the Fig. 2-a, it is observed that the tensile strength decreases with the increase in barrel temperature for lower value of screw speed and for higher value of screw speed, the tensile strength increases with increase in barrel temperature.

Table 4: Optimum process parameters

Parameters	Responses	
	TS (MPa)	TM (MPa)
Barrel Temperature (A), °C	130	150
Screw Speed (B), rpm	25	25
Die Temperature (C), °C	145	165

From the Fig. 2-b it is found that the tensile strength decreases and then increases with the increase in barrel temperature and die temperature. The maximum tensile strength is obtained at lower barrel temperature and higher die temperature.

Fig. 2-c shows that the tensile strength first decreases and then increases with the increase in screw speed and die temperature. The maximum tensile strength is obtained at minimum screw speed and maximum die temperature.

Fig. 3 shows the influence of process parameters on Tensile Modulus. Fig. 3-a shows that tensile modulus decreases with increase in barrel temperature at lower screw speed and increases with increase in barrel temperature at higher screw speed. The maximum tensile modulus is obtained at lower barrel temperature and screw speed.

Fig. 3-b shows that tensile modulus increases with increase in barrel temperature at lower die temperature and decreases with increases barrel temperature at higher die temperature. The maximum tensile modulus is obtained at lower barrel temperature and higher die temperature.

Fig. 3-c shows that the modulus values decreases then increases with increase in screw speed and die temperature. Irrespective of the screw speed, the modulus increases with increases in die temperature.

5 CONCLUSIONS

HDPE filaments suitable for 3DP of required diameter are extruded using single screw extrusion process based on Taguchi's L9 OA. Tensile test is conducted to find the tensile strength and tensile modulus of the extruded filaments. ANOVA reveals that barrel temperature and screw speed are most significantly contributing towards tensile strength and screw speed and die temperature towards tensile modulus. Mathematical models were formulated based on Response Surface Methodology and response surface plots are drawn to find influence of process parameters on the output response and the results are as follows:

- Tensile strength is maximum for minimum barrel temperature; maximum die temperature and minimum screw temperature.
- Tensile modulus is maximum for intermediate barrel temperature; minimum screw speed and maximum die temperature.
- At lower screw speed, with the increase in barrel temperature both tensile strength and tensile modulus decreases and vice versa at high screw speed.
- Increase in die temperature results in increase of tensile strength and tensile modulus.
- Maximum tensile strength and tensile modulus is observed at lower screw speed.

References

[1] Sood A.K., Ohdar R.K., Mahapatra S.S., Parametric appraisal of mechanical property of fused deposition modeling processes parts, *Materials and Design*, **31** (2010) 287-295.

[2] Singh K., Singh B.R., Singh H., Development of rapid tooling using fused deposition modeling: a review, *Rapid Prototyping Journal*, **22** (2016) 281-299.

[3] Song Y., Li Y., Song W., Yee K., Lee Y., Tagarielle V.L., Measurements of mechanical response of unidirectional 3D-printed PLA, *Materials and Design*, **123** (2017) 154-164.

[4] Mohamed O.A., Masood S.H., Bhowmik J.L., Experimental investigation of time-dependent mechanical properties of PC-ABS prototypes processes by FDM additive manufacturing process, *Materials letters*, **193** (2017) 58-62.

[5] Espin M.D., Forcada J.M.P., Granada A.A.G., Liuma J., Borros S., Reyes G., Mechanical property characterization and simulation of fused deposition modeling polycarbonate parts, *Materials and Design*, **83** (2015) 670-677.

[6] Zaldivar R.J., Witkin D.B., McLouth T., Patel D.N., Schmitt K., Nokes J.P., Influence of processing and orientation print effects on the mechanical and thermal behavior of 3D-Printed ULTEM® 9085 material, *Additive Manufacturing*, **13** (2017) 71-80.

[7] Singh R., Singh J., Singh S., Investigation for dimensional accuracy of AMC prepared by FDM assisted investment casting using nylon-6 waste based reinforced filament, *Measurement*, **78** (2016) 253-259.

[8] Marcinacinova L.N., Kuric I., Basic and advanced materials for fused deposition modeling rapid prototyping technology, *Manufacturing and Industrial Engineering*, **11** (2012).

[9] Singh S., Ramakrishna S., Singh R., Material issues in additive manufacturing: A review, *Journal of Manufacturing Processes*, **25** (2017) 185-200.

[10] Zhil'tsova T.V., Oliveira M.S.A., FerreiraJ.A.F., Relative influence of injection molding processing conditions on HDPEacetabular cups dimensional stability, *Journal of Material Processing Technology*, **209** (2009) 3894-3904.

[11] Elduque A., Elduque D., Javierre C., Fernandez A., Santolaria J., Environmental impact analysis of injection molding process: analysis of the processing of high-density polyethylene parts, *Journal of cleaner Production*, **108** (2015) 80-89.

[12] Abeykoon C., Single screw extrusion control: A comprehensive review and directions for improvement, *Control Engineering Practice*, **51** (2016) 69-80.

[13] Singh R, Singh N, Bedi P, Polymer single screw extrusion with metal powder reinforcement, Reference Module in Materials Science and Materials Engineering, Oxford Elsevier (2016) 1-18.

[14] Sorroche J.V., Kelly A.L., Brown E.C. Gough T., Abeykoon C., The effect of melt viscosity on thermal efficiency for single screw extrusion of HDPE, *Chemical Engineering Research and Design*, **92** (2014) 2404-2412.

[15] Chockalingam K., Jawahar N., Chandrasekar U., Ramanathan K.N., Establishment of process model for part strength in stereolithography, *Journal of Material Processing Technology*, **208** (208) 348-365.

[16] Cheremisinoff N.P., Polymer Characterization – Laboratory Techniques and Analysis, Noyes Publication, (1996).

[17] Ferg E.E., Bolo L.L., A correlation between the variable melt flow index and the molecular mass distribution of virgin and recycled polypropylene used in the manufacturing of battery cases, *Polymer Testing* , **32** (2013) 1452–1459.