Process Parameter Optimization in Fused Deposition Modeling (FDM) Using Response Surface Methodology (RSM)

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Abstract

Fused Deposition Modeling (FDM) is a widely adopted additive manufacturing process to produce complex 3D structures and it is typically used in the fabrication of biodegradable materials e.g. PLA/PHA for biomedical applications. However, FDM as a fabrication process for such material needs to be optimized to enhance mechanical properties. In this study, dogbone and notched samples are printed with the FDM process to determine optimum values of printing parameters for superior mechanical properties. The effect of layer thickness, infill density, and print bed temperature on mechanical properties is investigated by applying response surface methodology (RSM). Optimum printing parameters are identified for tensile and impact strength and an empirical relation has been formulated with response surface methodology (RSM). Furthermore, the analysis of variance (ANOVA) was performed on the experimental results to determine the influence of the process parameters and their interactions. ANOVA results demonstrate that 44.7% infill density, 0.44 mm layer thickness, and 20C° printing temperatures are the optimum values of printing parameters owing to improved tensile and impact strength respectively. The experimental results were found in strong agreement with the predicted theoretical results.

1. Introduction

Fused deposition modeling (FDM) is a layer-wise additive manufacturing process developed by Stratasys® to fabricate customized geometric structures directly from a digital STL file[1]. FDM uses polymers in wire form as its input material which is extruded through a heated nozzle and fused by cooling in ambient air on a printing bed gradually in the form of layers to build the part directly from the digital geometric data [2]. FDM is popular for its simple printing mechanism, material flexibility, and low cost which makes the technology very attractive for 4D Printing [3]. FDM is currently used in the printing of thermoplastics e.g. polyethylene, polypropylene, Teflon, acrylonitrile butadiene styrene or (ABS), high impact polystyrene resin (HiPS), polyethylene terephthalate glycol (PETG), polyamide (PA) generic name nylon, polyether ether ketone (PEEK) and polylactic acid (PLA), composites, ceramics and metal powder for rapid prototyping, automobile, aerospace, mold, and pattern design, and biomedical applications [2, 4–5]. Among the aforementioned materials, Polylactide (PLA) offers several advantages such as good mechanical properties, being environmentally benign, and that complies with government regulations on the use of non-degradable thermoplastics. Due to this, this material is extensively used in food packaging, medical implants, and many other consumer goods. Additionally, PLA is a biodegradable thermoplastic polymer which makes it a suitable fabrication material for biomedical implants and orthopedics parts. However, its lower mechanical properties make it inadequate for certain high-strength applications. This limitation can be overcome by modifying PLA through the addition of PHA (Polyhydroxyalkanoate) to enhance mechanical properties. A study proposed by Chiulan I et al. [4] discovered that mechanical properties of PLA can be ameliorated with the addition of PHA. Therefore, PLA blended with PHA co-polymers is the most suitable option because such kind of polymers does not influence the composability of PLA. PLA and its blends show good mechanical properties, due to which,

PLA/PHA material has been extensively studied for use in packaging and medical applications especially for fabricating scaffold, dental implants, and bio-resorbable screws for bone fracture.

FDM is a flexible additive manufacturing process with various printing parameters such as layer thickness (LT), build orientation, % infill density, printing bed or substrate temperature air, shell count, top thickness and bottom thickness, infill patterns, raster angle (RA), and raster scheme. These parameters can strongly affect the quality as well as the mechanical properties of the printed parts. Among all aforementioned parameters, some parameters have more significant influence than others. Popescu et al. [5] analyzed the number of parameters and suggested solutions to minimize the number of experiments and methods that optimize and give the best combination of parameters for the ideal mechanical properties. B. Tymrak et. al.[6] used 'RepRap' type printer to evaluate tensile strength of PLA and ABS specimens with varying layer thickness and it was concluded that ABS samples showed a negligible difference even at the lower layer thickness of 0.2 mm samples have marginally higher UTS. On the other hand, layer thickness had a substantial effect on UTS in PLA samples. Santhakumar et al.[7] tried to enhance the toughness of Polycarbonate by improving the FDM process parameter settings using Taguchi method in which layer thickness, build orientation, and raster width were studied with three levels. Experimental results demonstrated the layer thickness, 0.254 mm; build orientation, 30°; raster width, 0.904 mm, and raster angle 60° as optimum parameters. Design of experiment and response surface regression technique has been implemented in process parameter optimization for the machining process it can be extended for additive manufacturing [8]. Sood et al. [9] reported improved tensile and impact strengths of the samples by altering the printing parameters like layer thickness (0.1270, 0.1780 and, 0.2540), orientation, RA, raster width, and air gap by using the RSM technique. It was observed that maximum impact strength was achieved with increasing layer thickness to 0.2540 mm, and higher tensile strength reported against decreasing layer thickness to 0.1270 mm. Shubham et al.[10] investigated the effect of layer thickness on the impact strength of PLA/PHA composite. Increasing layer thickness improves the impact strength due to uniformity of molecular bond and homogeneity within the layers. Carneiro et al.[11] investigated the mechanical performance by printing samples at varying infill density of 20%, 60%, and 100%. There was a linear relationship between Young's modulus and infill density and higher infill density increased UTS. Joseph et al.[12] recognized that low infill density leads to print a part in less time and low material usage and 3D printed parts with low FD provide higher impact strength due to porous structures as the flexibility increases in these parts. Isfahani et al.[13] found that decreasing FD creates hollow spaces which reduce the density of fiber, giving rise to the impact strength. Martin Spoerk et al. [14] reported that the optimal adhesion of the PLA and ABS printed parts to the bed of the printer can be achieved by increasing the bed temperature above the glass transition temperature (TG) of the printing filament. When the bed temperature increases above the material's TG, it reduces the surface tension between the printing filament and the printing bed. This phenomenon leads to the larger contact area and consequently better adhesion is achieved between the filament and the bed.

The proposed study is an attempt to improve the tensile and impact strength of PLA/PHA composite by optimizing process parameters (layer thickness, % infill density, and printing bed temperature) using

response surface methodology (RSM). Enhanced results of mechanical properties could be used to expand the scope of PLA/PHA composite, especially to medical applications.

2. Methodology

2.1 Material, Printer, Specimen

Wire filament made of polymer composite of Polylactic acid (PLA) and Polyhydroxyalkanoates (PHA) from Color Fabb Netherlands was used in FDM experiments. The company’s provided material specifications are illustrated in table 1.

Table 1. Material Specifications

Material	ColorFabb PLA/PHA
Diameter	1.75mm
Density (D.)	1220;1440 g·c. m-3
Glass. Transition. (GT) Temperature	55 C

The CREALITY CR-10S5 3D printer was used to print dogbone and notched shaped specimens in this study as shown in Fig 1. The printer is made of a special aluminum frame with a print bed size up 500×500×500 mm and dual Z-Axis lead screws filament to control the accuracy of printing. Specimens for tensile and impact strength tests shown in Fig 2 were designed in SolidWorks® according to ASTM D638-14 and D256-10 respectively [15][16].

2.2. Response Surface Methodology (RSM)

Response surface methodology (RSM) is a mathematical and statistical technique to evaluate, improve, and optimize the desired response influenced by independent variables. Optimization of process parameters as well as the relationship between outcome response and input parameters can be handled efficiently through RSM. The relationship between tensile and impact strength of PLA/PHA composite is a function of the printing parameters such as layer thickness, infill density, and print bed temperature, which can be expressed as the regression model with a second-order derivation of a mathematical equation. A Box-Behnken (BB) statistical model was developed using response surface methodology to evaluate the mechanical properties as a function of the % infill density, print bed temperature, and layer thickness. The data were analyzed by the Design of Experiment (DoE) and Analysis of Variance (ANOVA). The design of experiments with a combination of three variables for tensile and impact tests are presented in Table 2. Adequate contact between the layer bottom and print bed temperature is maintained with adhesive tape.

Table 2: RSM input parameters and processing conditions for FDM Printing

Runs No	Layer thickness. (mm)	Infill Density (%)	Print Bed Temperature (C°)	Fixed Parameters	
1	0.34	55	20	Bottom - top thickness. (mm)	0.6
2	0.6	20	40		
3	0.34	37.5	40	Print speed. (mm/s)	40
4	0.34	20	60		
5	0.6	37.5	60	Printing. temperature C°	200
6	0.34	37.5	40		
7	0.08	55	40	Nozzle diameter (mm)	0.4
8	0.6	55	40		
9	0.6	37.5	20	Built orientation (°)	0
10	0.34	55	60		
11	0.34	37.5	40	Infill pattern	Grid (inner), Line (top & bottom)
12	0.08	37.5	20		
13	0.08	37.5	60	Shell count	3
14	0.34	37.5	40		
15	0.08	20	40	Wall thickness (mm)	1.2
16	0.34	37.5	40		
17	0.34	20	20	Test Speed	1mm/min

Several other printing parameters were taken as constants during the experiments based on the previous literature.

2.3. Printing Procedure

After identifying the significant process parameters in Box-Behnken design, the FDM printing experiments were conducted against each combination of input variables, (%infill density, layer thickness, and print bed temperature) as shown in Table 2. Apart from input variables, there are several fixed parameters and print conditions as illustrated in the same table, however, their consequences on mechanical properties are not considered during this experimental study. 17 dogbone specimens for tensile and 17 notched specimens for impact tests were printed on the prescribed processing parameters as shown in Fig. 3. Material filaments and the fabricated specimens were kept at a controlled temperature in air-tight packaging.

Universal Testing Machine (AG100kNX) was used to perform tensile testing on dogbone specimens according to the tensile test standard ASTM 638-14 at 25C° temperature and tensile strength (σ_t) is calculated from stress-strain graph [15]. Moreover, impact tests were carried out according to test standard ASTM D256-10 [16] using H pendulum Izod/Charpy Impact Testing Machine (GT-7045-HM). Impact tests were performed at 135° with 1J hammer and Izod impact energy is determined in J/m. Fig. 4 shows the specimen condition after testing.

3. Results And Analysis

Experimental values were obtained after tests as illustrated in Fig. 5 and 6 for tensile and impact strength respectively. RSM was applied to investigate linear, interaction & quadratic effect of independent parameters i.e.% infill density, layer thickness, and bed temperature on the impact energy (E_i) and tensile strength (σ_t) of PLA/PHA composite specimens printed with FDM process. Regression equations were established by the fitting of obtained experimental values to several models (linear, 2FI & quadratic). Various tests i.e. the sequential model sum of squares (SS), lack of fit (LF), and model summary statistics (MS) were used to estimate the adequacy of the model [17]. SS, LF test, and MS suggest the desired model for all responses, therefore, these tests were conducted for each response on prescribed processing parameters in Table 2.

X-Ray Powder Diffraction (XRD) was performed to analyze material homogeneity and composition. The results, depicted in Fig 7, showed an XRD peak of PLA/PHA specimen reported at $2\theta = 16.5^\circ$ which is consistent with the reported literature [18].

3.1. Tensile Strength

The sequential model with sum of squares was suggested based on p-value with $P < 0.05$ [19]. SS for the tensile test showed that p-value is less than 0.05 for both the linear and quadratic models as presented in Table 3.

Table 3: SS for Tensile Strength

Sources	Sum of squares	Df	Mean Square	F Value	P-value	
<i>Mean</i>	11932.42	1	11932.42			
<i>Linear</i>	410.93	3	136.98	2.87	0.0769	
<i>2FI</i>	23.09	3	7.70	0.1290	0.9407	
<i>Quadratic</i>	459.66	3	153.22	7.82	0.0123	Suggested
<i>Cubic</i>	108.98	3	36.33	5.15	0.0736	Aliased
<i>Residual</i>	28.19	4	7.05			
<i>Total</i>	12963.28	17	762.55			

LF test suggested the model based on p-value with $P > 0.05$ [20]. The model suggested for tensile strength by LF is the quadratic model. The quadratic model for tensile strength showed a non-significant lack of fit as its value is 0.0736 which is higher than 0.05 as presented in Table 4.

Table 4: Lack of Fit (LF) Tensile Strength

Sources	Sum. of Squares	Df	Mean Square	F-Value	P-value	
<i>Linear</i>	591.73	9	65.75	9.33	0.0230	
<i>2FI</i>	568.64	6	94.77	13.45	0.0126	
<i>Quadratic</i>	108.98	3	36.33	5.15	0.0736	Suggested
<i>Cubic</i>	0.0000	0				Aliased
<i>Pure Error</i>	28.19	4	7.05			

In model summary statistics (MS), from a previous study, it was found that an RS value greater than 0.75 is acceptable [19]. RS value is 0.8669 which is higher than 0.75 as shown in Table 5.

Table 5. Summary Statistics Tensile Strength Test

Source	Set.Dev.	RS	Adjusted RS	PRESS	
<i>Linear</i>	6.91	0.3986	0.2599	1249.36	
<i>2FI</i>	7.73	0.4210	0.0737	2865.61	
<i>Quadratic</i>	4.43	0.8669	0.6958	1787.75	Suggested
<i>Cubic</i>	2.65	0.9726	0.8906		Aliased

3.2. Tensile Strength (ANOVA)

ANOVA for tensile test obtained data gives F-value of 5.07 which indicates the significance of the model as shown in Table 6. All terms whose p-value is less than 0.05 ($P < 0.05$) are significant. In this case, the linear effect of layer thickness and the quadratic effect of layer thickness is significant. Values greater than 0.05 demonstrate that terms did not affect the response. “Lack of Fit LF-value” of 0.073 suggests the Lack of Fit is non-significant.

Table 6: ANOVA for Tensile Strength

Source	Sum of Squares	Df	Mean Square	F-value	P-value	
<i>Model</i>	893.69	9	99.30	5.07	0.0219	Significant
<i>A- Layer thickness</i>	370.06	1	370.06	18.88	0.0034	
<i>B- Infill density</i>	40.86	1	40.86	2.09	0.1920	
<i>C- Bed Temperature</i>	0.0171	1	0.0171	0.0009	0.9773	
<i>AB</i>	7.98	1	7.98	0.4072	0.5437	
<i>AC</i>	3.31	1	3.31	0.1690	0.6933	
<i>BC</i>	11.80	1	11.80	0.6021	0.4632	
<i>A²</i>	411.67	1	411.67	21.01	0.0025	
<i>B²</i>	16.08	1	16.08	0.8208	0.3951	
<i>C²</i>	51.20	1	51.20	2.61	0.1501	
<i>Residual</i>	137.18	7	19.60			
<i>Lack of Fit</i>	108.98	3	36.33	5.15	0.0736	Not significant

The obtained regression equation w.r.t coded factors to predict the influence of layer thickness, infill density, and bed temperature on tensile strength without non-significant parameters, is given below:

$$\sigma_t = 28.59 + 6.80 \times A + 2.26 \times B + 0.04 \times C - 1.41 \times A \times B - 0.91 \times A \times C - 1.72 \times B \times C - 1.72 \times B \times C - 9.89 \times A^2 + 1.95 \times B^2 + 3.49 \times C^2 \quad \text{Eq (1)}$$

According to ANOVA, layer thickness and % infill density play a vital role in the tensile strength of printed samples shown in Fig. 8 and table 6.

3.3. Impact Strength

The sequential model with sum of squares was suggested on the basis of p-value with $P < 0.05$ [21]. SS indicates that for impact strength the p-value is less than 0.05 for the quadratic model as shown in Table 7.

Table 7: SS for Impact Strength

Sources	Sum of squares	Df	Mean Square	F Value	P-value	
<i>Mean</i>	1412.87	1	1412.87			
<i>Linear</i>	93.57	3	31.19	1.76	0.2042	
<i>2FI</i>	24.05	3	8.02	0.3886	0.7638	
<i>Quadratic</i>	153.46	3	51.15	6.78	0.0177	Suggested
<i>Cubic</i>	34.32	3	11.44	2.48	0.2008	Aliased

Lack of fit test suggests the model based on p-value with $P > 0.05$ [22]. The model suggested for impact strength by Lack of fit is the quadratic model as shown in Table 8. The quadratic model for impact strength showed a non-significant lack of fit as its value is 0.2008 which is higher than 0.05.

Table 8: Lack of Fit Test for Impact Strength

Sources	Sum of Squares	Df	Mean Square	F-Value	P-value	
<i>Linear</i>	211.83	9	23.54	5.09	0.0659	
<i>2FI</i>	187.78	6	31.30	6.77	0.0426	
<i>Quadratic</i>	34.32	3	11.44	2.48	0.2008	Suggested
<i>Cubic</i>	0.0000	0				Aliased

Earlier it was reported that RS value greater than 0.75 is acceptable in model summary statics (MS) [23]. The model suggested for impact strength by summary statistics is the quadratic model as presented in Table 9.

Table 9: Summary Statistics of Impact Strength

Source	Set.Dev.	RS	Adjusted RS	Predicted RS	PRESS	
<i>Linear</i>	4.21	0.2889	0.1248	-0.3248	429.10	
<i>2FI</i>	4.54	0.3632	-0.0190	-1.5915	839.37	
<i>Quadratic</i>	2.75	0.8370	0.6273	-0.7847	578.04	Suggested
<i>Cubic</i>	2.15	0.9429	0.7717			Aliased

3.4. Impact Strength (ANOVA)

From ANOVA for impact test obtained data, the model's F-value of 3.99 suggests the model is significant as shown in Table 10. All terms of the model whose p-value is less than 0.05 are termed as significant as shown in Table 4-9. The linear effect of layer thickness in significant terms compares to the remaining

terms. $P > 0.05$ demonstrates that terms are non-significant. The "Lack of Fit F-value" of 2.48 suggests that lack of fit is non-significant.

Table 10: ANOVA for Impact Strength

Source	Sum of Squares	Df	Mean Square	F-value	P-value	
<i>Model</i>	271.08	9	30.12	3.99	0.0407	Significant
<i>A- Layer thickness</i>	76.20	1	76.20	10.10	0.0155	
<i>B- Infill density</i>	15.88	1	15.88	2.10	0.1901	
<i>C- Bed Temperature</i>	1.50	1	1.50	0.1984	0.6695	
<i>AB</i>	9.77	1	9.77	1.29	0.2926	
<i>AC</i>	0.2209	1	0.2209	0.0293	0.8690	
<i>BC</i>	14.06	1	14.06	1.86	0.2144	
<i>A²</i>	81.06	1	81.06	10.75	0.0135	
<i>B²</i>	52.40	1	52.40	6.95	0.0336	
<i>C²</i>	19.91	1	19.91	2.64	0.1482	
<i>Residual</i>	52.81	7	7.54			
<i>Lack of Fit</i>	34.32	3	11.44	2.48	0.2008	Not significant

Regression equation, w.r.t coded factors to predict influence of layer thickness, print bed temperature, and Infill density on impact strength without non-significant parameters, is given below:

$$E_i = 11.818 + 3.08625 * A + 1.40875 * B + -0.4325 * C + 1.5625 * AB + -0.235 * AC + 1.875 * BC + -4.38775 * A^2 + -3.52775 * B^2 + 2.17475 * C^2 \quad \text{Eq (2)}$$

Analysis of Variance reported that % infill density and layer thickness has a substantial effect on the impact strength of printed notched specimens as shown in Fig. 9.

3.5. Process Parameter Optimization

Numerical optimization was used to find out optimum levels of independent parameters. By using the desirability function (DF), RSM identified an arrangement of parameters to optimize several responses [19] and provide the responses which are most significant and will give the maximum tensile and impact strength at optimized parameters as presented in table 11.

Table 11: prediction of responses

<i>Factor</i>	<i>Na.me</i>	<i>Optimize Level.</i>	<i>Low level.</i>	<i>High level.</i>	<i>Tensile strength</i> <i>MPa</i>	<i>Impact strength</i> <i>J/m</i>
A.	Layer thickness.	0.4443	0.0800	0.6000	35.27	14.51
B	Infill density	44.76	20.00	55.00		
C	Bed temperature	20.00	20.00	60.00		

3.6. Verification of Experiment

RSM suggested the optimum levels of layer thickness, % infill density & bed temperature which were 0.44mm, 44.76 %, and 20 °C temperature respectively. These predicted values were verified to check the competence of the obtained equations. Predicted and experimental values of tensile and impact strength at optimal conditions are shown in Table 12. The stress-strain curve for tensile test specimen under the optimal level of parameters is depicted in Fig 10.

Table 12: Verification of experiments

Sr. No	Responses	Predicted Value	Experimental Value	Percentage Error
1	Tensile Strength (MPa)	35.27	32.99	6.0%
2	Impact Strength (J/m)	14.51	14.13	2.68%

4. Conclusion

The proposed research intended to enhance the mechanical properties of PLA/PHA composite in fused deposition modeling (FDM) based additive manufacturing. Tensile and impact specimens were printed by the FDM process to determine the optimum process parameters with the application of response surface methodology (RSM). Three parameters namely layer thickness, %infill density, and print bed temperature were treated as the key variables in the RSM model while other parameters were kept constants. It is established that, optimize parameters (0.44mm layer thickness, 44.7% infill density, and 20C° print bed temperature) computed by RSM provided the same tensile strength with a minimal difference at low % infill density, which helps the designers with decision-making to reduce the production cost. Following conclusions are drawn from this study:

- Layer thickness has the most significant influence on the mechanical properties (tensile and impact) of PLA/PHA specimens followed by % infill density and print bed temperature.
- Application of response surface methodology (RSM) in FDM effectively reduced the print runs and optimized the printing parameters to reduce manufacturing time and cost with the attainment of substantial structural strength.

- Maximum tensile strength is reported as 39.8 MPa with 0.34 mm layer thickness and 55 % infill density. However, RSM gives 35.27 MPa with 0.44 mm layer thickness and 44.75 % infill density which minimizes the printing time and material consumption respectively within the given range of data.
- Results of verification experiments reported a negligible % error between the experimental result and theoretically predicted values. Experimental results proved the validation of RSM equations for all responses.
- The regression model and corresponding equations are therefore satisfactory and might be used in future research which shows that RSM is a good optimizing technique.

Declarations

Authors Contribution;

Muhammad Arsalan Munir and Muhammad Qasim Zafar performed the complete printing trial and wrote initial manuscript under the supervision of Dr. Salman Mustafa. Dr. Farrukh Arsalan Siddiqui and Hafiz Muhammad Asif Javed supervised the mechanical testing and Dr. Muhammad Arif reviewed the manuscript.

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It is solemnly declared that there is no competing interest among authors.

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Figures

Figure 1

Typical printing mechanism of FDM using PLA/PHA filament.

Figure 2

Design of tensile and impact specimen according to ASTM standard

Figure 3

FDM printed specimens for mechanical properties a) Tensile, b) Impact

Figure 4

Notch and dogbone have broken samples after impact and tensile respectively.

Figure 5

Tensile testing result for 17 experiments.

Figure 6

Impact testing results for 17 experiments

Figure 7

XRD pattern of PLA/PHA 3D printed sample

Figure 8

Tensile strength contour 3D surface plot

Figure 9

Impact strength contour 3D surface plot

Figure 10

Stress-strain curve of tensile sample for optimized parameters. The theoretical results are considered as a benchmark. The variation between theoretical and practical results is due to the limitations of both UTM & Izod testing machines.