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Influence of manufacturing parameters on the strength of PLA parts using Layered Manufacturing technique: A statistical approach

K.G. Jaya Christiyan[a*], U. Chandrasekhar[b], N. Rajesh Mathivanan[c], K. Venkateswarlu[d]

[a] M S Ramaiah Institute of Technology, Bangalore -560054.
[b] Vel-Tech University, Chennai -600062.
[c]P E S Institute of Technology, Bangalore 560 085
[d]CSIR-National Aerospace Laboratories, Bangalore-560017.
*E-mail:jayachristiyan@msrit.edu

Abstract. A 3D printing was successfully used to fabricate samples of Polylactic Acid (PLA). Processing parameters such as Lay-up speed, Lay-up thickness, and printing nozzle were varied. All samples were tested for flexural strength using three point load test. A statistical mathematical model was developed to correlate the processing parameters with flexural strength. The result clearly demonstrated that the lay-up thickness and nozzle diameter influenced flexural strength significantly, whereas lay-up speed hardly influenced the flexural strength.

1. Introduction

Fused deposition modeling (FDM) is one of the fast-growing rapid prototyping (RP) technologies. This technology helps designers to visualize a 3D digital model into a physical part of any complex shape and can be fabricated by the tool-less manufacturing with less manufacturing time and cost. [1–5]. Hence, RP is a powerful technology to manufacture full-scale models that have not gained much consideration because of compatibility of available materials [6, 7]. This FDM technology is introduced by STRATASYS Inc., in 1990's. A low-cost 3D printer are introduced with the same technology (FDM) and called as 3D printing. In this 3D printing technology, more than twenty thermoplastic materials are used for the manufacturing of engineering and medical components. Acrylonitrile butadiene styrene (ABS) and Polylactic Acid (PLA) are the most commonly used thermoplastic material in 3D printers. But PLA is degradable with carbon dioxide (CO2), water (H2O) and humus so it is called green polymer material. PLA materials are extracted from renewable resources, such as corn-starch, sugar cane, tapioca roots or even potato starch. The filament manufactured from PLA is low cost, superior in strength and has a lower melting point compared to ABS. Due to the above advantages, PLA material is considered for the present study.

FDM process is simple and economical to produce components with high quality. However, light weight and high specific mechanical properties are a major concern. For parametric analysis and empirical modeling of the process, a central composite design (CCD) methodology is used to reduce the number of experiments and to study the effect of parameters including their iteration [9]. Extensive research is done to investigate the effect of layer thickness in the field of FDM. F Rayegani et al. [10] have studied four process parameter (part orientation, air gap, raster angle and raster width) with differential evolution methodology to predict the optimal process parameters to attain best tensile strength. The mathematical model of the surface response of the tensile strength with respect to the different process parameters is studied. It is observed that the orientation and raster angle affects the tensile strength of the FDM part considerably when compared to other parameters. Liu Xinhua et al. [11] have recorded the five process parameters (layer thickness, fill speed, nozzle temperature, fill style, and raster width) to predict the accuracy (of what physical property measurement?) of the thin plate a portable non-contact 3D laser scanner experimentally. Two analytical methods are used to optimize the process parameters to reduce the experimentation samples such as signal to noise ratio and analysis of variance (ANOVA). The experimental results recorded by the optimal process parameters are validated by the theoretical method. It is believed that better accuracy is achieved with lesser layer thickness.

Said et al. [12] have studied five different raster orientations and suggested that it causes alignment of polymer molecules along the direction of deposition during fabrication of the flexural, tensile and impact strength. Ahn et al. [13] have reported that parameters such as air gap and raster orientation significantly affect the tensile strength of FDM built part as compared to other three parameters such as raster width, model temperature, and colors. In addition, built parts showed anisotropic properties subjected to build orientation as far as tensile and flexural strength are concerned. Anitha et al. [14] have evaluated the three critical parameters (layer thickness, road width, and printing speed) affecting the quality of FDM prototype and concluded that the layer thickness is a predominant parameter, as it affects 51.57 % (of what?) at 99 % of significance. The other parameters like road width and speed have less influence parameter and contribute 15.57 % and 15.83 % at 99 % level of significant, respectively. It has been noticed that the material is extruded through the nozzle; it cools as it passes through the tip of the nozzle. During this stage, the material transforms to glass transition phase developing inner stresses causing irregular deposition. Crack formation occurs due to the irregular deposition the interlayer and the intralayer of the part, causing the part to fail or delaminate. Wang et al.[15] have also indicated that the glass transition phase is responsible for the reduction in part strength and part deformation.

The above studies clearly suggest that critical factors (which ones? – they can be mentioned here)influencing the process parameters of PLA parts by 3D printing technique plays a vital role in improving the mechanical properties of the component/part. Though enough research has been done on orientation, nozzle temperature, air gap and other factors, but limited research is done on nozzle diameter, effect of lay-up thickness and lay-up speed. Therefore, it is essentially required to study optimization and enhancement of the mechanical properties of PLA materials prepared by a 3D printing process.

2. Experimental methods and process

In this work, three major factors were considered such as lay-up thickness, lay-up speed, and nozzle diameter. The lay-up thickness is the thickness of one layer deposited by the nozzle during one bead. It can be varied based on the nozzle diameter. Lay-up speed was the speed at which the printing is done and measured in mm/s. Nozzle diameter regulates the flow of material, varying the nozzle diameter, the thickness of the lay-up can be monitored. The levels of varying and fixed factors are presented in Table 1 and 2, respectively.

Table: 1 Levels of factors

Factor	Symbol	Unit	Levels		
			Low (-1)	Centre (0)	High (1)

Lay-up thickness	*(A)*	*mm*	0.2	0.25	0.3
Lay-up Speed	*(B)*	*mm/s*	30	40	50
Nozzle Diameter	*(C)*	*mm*	0.4	0.5	0.6

Table: 2 Fixed Factors

Factor	Unit	Values
Part Fill style	*degree*	45/-45
Lay-up Temperature	*°C*	180
Bed temperature	*°C*	40
Infill	*%*	70

The heating coil around the nozzle heated the filament and start melting below its melting point. The thermoplastic material was extruded due to the pressure induced by the rotation of the rollers (feeders) of the nozzle. The nozzle moves in x and y direction according to the program and deposits the material on the table. The table moves in downward (z) direction when the layer is completed. The same procedure is repeated until the part is manufactured.

The samples were prepared according to the ASTM D790 standards. The width of the sample was maintained at 12.5 – 12.8 mm, while the length was maintained at 126.9 – 127.1 mm. The thickness of the sample was in the range of 3.2 – 3.3 mm. The samples were modeled using Autodesk Inventor. The output of the sample from Autodesk Inventor was exported into .stl (Standard Triangulation Language) file format. The .stl file was imported to the Slice3r open source 3D printing software. There the sample was oriented and sliced into a number of layers. The sliced data was transferred to a 3D printing machine. For the preparation of the samples, PLA filament was used. The temperature of the nozzle was kept at ~190° C and the bed was kept at room temperature ~ 27° C. The printing set up is shown in figure 1.

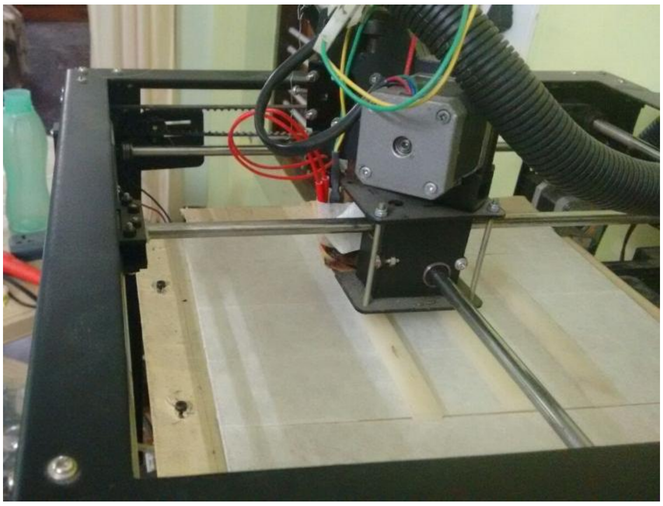

Figure: 1 Open source 3D printing machine

For conducting three point bend test, a MECMESIN machine was used and shown in figure 2. The testing was carried with a load cell of 10kN. The test was conducted according to the ASTM standard D790 with a crosshead speed of 1 mm/min. Experiments were conducted during the single session. The flexural test was conducted at room temperature. The fixture of the 3 point was designed as per the ASTM standard. The samples were kept in two supports and the middle was loaded with a full

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force (N) until the test sample fracture. The maximum stress acts at the center point where the full load is acting. The distance between the supports was 100 mm and 5 mm nose radius spherical tool was used for loading. The experiment was stopped when the sample broke.

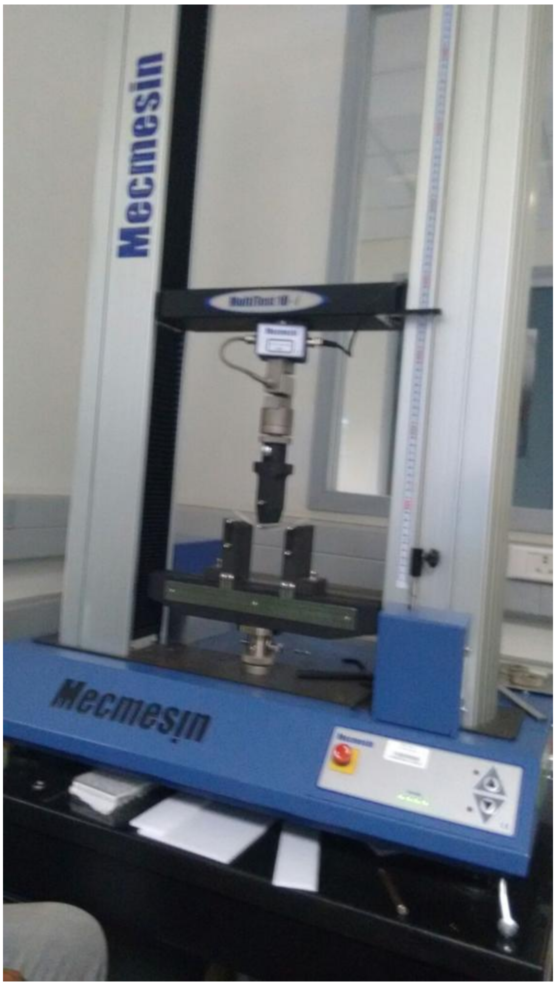

Figure: 2 MECMESIN 3 Point bending machine

Response Surface Methodology (RSM) is a method of finding the possibility of an independent manufacturing parameter in the quantities form as indicated in equation 1.

$$y=f(x_1,x_2,x_3,\ldots\ldots x_n)\pm\varepsilon \quad (1)$$

Where y is the response (yield of the process), f is the response function, $x_1,x_2,x_3,\ldots\ldots x_n$ were the different independent parameters and ε is error observed in the experimentation. By plotting the expected yield of the process of "y", a surface was obtained is known as the response surface. The form of response function "f" and the independent manufacturing parameters is unknown. The relation between theses may be very complicated. The RSM plays a vital role to do a lower order polynomial equation in some region of the independent manufacturing parameters; the equation 1 for the function of the first order model can be rewritten as shown in equation 2.

$$y= A_0+A_1 x_1+A_2 x_2+\cdots+A_n x_n\pm\varepsilon \quad (2)$$

However, there is a curvature appears in the system, then a higher order polynomial quadratic response surface model equation 3 may be used:

$$y = A_0 + \sum_{i=1}^{k} A_i x_i + \sum_{i=1}^{k} A_{ii} x_i^2 + \sum_{i<j} \sum A_i x_i x_j + \epsilon \tag{3}$$

The objective of the RSM is to predict a reasonable approximation of the response function and the independent manufacturing parameters, but to locate the region of the nearest optimal value. The response analysis surface model, the combination of variables (factors) that gives a better surface model is studied in detail. Figure 4 represents the summarized sequential procedure of response surface design. The F- value generated by the ANOVA table was used to predict the significance check. To predict the probability of the greater value of the F-value is calculated and indicated with noise by p-value. Analysis of variance (ANOVA) is also performed to predict the proposed model by using the second order regression analysis were calculated and tabulated in Table 4. ANOVA gives an idea about the quadratic model for envisaging the flexural strength of samples with regression value p less than 0.05 were significant.

To develop the empirical model on flexural strength, an extensive study on the effect of manufacturing parameters, experiments are conducted based on Face centered central composite design (FCCCD). The influencing manufacturing parameters such as Lay-up thickness (A), Lay-up speed (B) and Nozzle diameter (C) on the samples subjected to flexural strength is investigated. This design makes the axis points in the middle of the faces of cube and need of only three levels for each factor is considered. The design expert 9 software was used for regression and graphical analysis. The optimum values of the selected variables were obtained by eliminating insignificant factors. ANOVA is performed to test the adequacy of the model.

The analysis was intended to enhance PLA parts with higher flexural strength. The significance of the regression model and the model coefficient was included data analysis. ANOVA was performed using 21 runs to investigate the influencing factors affecting the flexural strength of the parts. To obtain more accurate results each combination of the factors are repeated 3 times. The quadratic model for analysis of flexural strength is developed and the quadratic model in the form of ANOVA is given in Table 3.

Table: 3: Experimental data obtained from the FCCCD runs

Run No.	Factors			
	Lay-up thickness (A) mm	*Lay-up speed (B)* mm/s	*Nozzle diameter (C)* mm	*Flexural Strength (MPa)*
1	0.2	40	0.4	102.88
2	0.2	50	0.5	84.01
3	0.2	50	0.6	75.44
4	0.25	30	0.4	99.45
5	0.25	30	0.5	84.01
6	0.25	30	0.6	77.16
7	0.25	40	0.4	97.73
8	0.25	40	0.5	72.01
9	0.25	40	0.6	75.44
10	0.25	50	0.4	85.73

11	0.25	50	0.5	65.15
12	0.25	50	0.6	72.01
13	0.3	30	0.4	96.3
14	0.3	30	0.5	66.87
15	0.3	30	0.6	73.73
16	0.3	40	0.4	87.45
17	0.3	40	0.5	65.15
18	0.3	40	0.6	70.3
19	0.3	50	0.4	78.82
20	0.3	50	0.5	63.44
21	0.3	50	0.6	60.01

3. Results and Discussion

Subjecting the model to analysis, the factors affecting the flexural strength along with its interactions with others is also considered. The quadratic function of each variable is subjected to analysis. The degree of freedom is 13. From the quadratic model generated it is noted that a few factors are not influencing the flexural strength to a large extent. To improve the accuracy of the above model, factors which are insignificant need to be eliminated. The regression of the model indicates the relationship between the independent factors and the flexural strength to be *96.59%.* It is observed from the Table 4, factors; *A, B, C, AC and* C^2 are significant while the other factors are insignificant. The insignificant factors are eliminated by backward elimination method to improve the model.

Table : 4 ANOVA results of the quadratic model (before elimination)

Source	*df*	*Sum square*	*Mean square*	*F-value*	*p-value*	*Effect*
Model	13	2794.91	214.99	13.11	0.0024	Significant
A-Lay-up Thickness	1	288.24	288.24	17.57	0.0057	Significant
B-Lay-up Speed	1	177.85	177.85	10.84	0.0166	Significant
C-Nozzle Dia	1	146.89	146.89	8.96	0.0242	Significant
AB	1	2.000E-004	2.000E-004	1.219E-005	0.9973	Insignificant
AC	1	119.51	119.51	7.29	0.0356	Significant
BC	1	52.74	52.74	3.22	0.1231	Insignificant
A^2	1	0.27	0.27	0.016	0.9029	Insignificant
B^2	1	22.90	22.90	1.40	0.2820	Insignificant
C^2	1	376.07	376.07	22.93	0.0030	Significant
ABC	1	23.39	23.39	1.43	0.2775	Insignificant
A^2B	1	75.13	75.13	4.58	0.0761	Insignificant
A^2C	1	0.29	0.29	0.018	0.8981	Insignificant
AB^2	1	7.33	7.33	0.45	0.5288	Insignificant
AC^2	0	0.000				Insignificant
B^2C	0	0.000				Insignificant
BC^2	0	0.000				Insignificant
A^3	0	0.000				Insignificant
B^3	0	0.000				Insignificant
C^3	0	0.000				Insignificant
Residual	6	98.41	16.40			
Lack of Fit	1	98.41	98.41	2.812E+005	< 0.0001	significant
Pure Error	5	1.750E-003	3.500E-004			
Total	19	2893.33				

R^2 = 0.96598

$$Flexural\ Strength = 74.19 - 12 \times A - 9.43 \times B - 8.57 \times C - 5e^{-3} \times AB + 3.87 \times AC + 2.57 \times BC - 0.31 \times A^2 - 2.89 \times B^2 + 11.69 \times C^2 - 1.71 \times ABC + 6.85 \times A^2B - 0.43 \times A^2C + 2.14 \times AB^2 \quad (4)$$

The actual code factors A, B, C in the Eq. 4 is the actual factors of the transformed values, and hence the equation can be written as (5):

Flexural strength = 74.19 – 12 x Lay-up thickness - 9.43 x Lay-up speed - 8.57 x Nozzle diameter - 5e^{-3}*x (Lay-up thickness x Lay-up speed) +3.87 x(Lay-up thickness x Lay-up diameter) + 2.57 x (Lay-up thickness x Lay-up speed) - 0.31 x Lay-up thickness^2 - 2.89 x Lay-up speed^2 + 11.69 Nozzle diameter ^2- 1.71 x (Lay-up thickness x Lay-up speed x Nozzle diameter) + 6.85 x (Lay-up thickness^2x Lay-up speed) - 0.43 x (Lay-up thickness^2x Nozzle diameter) + 2.14 x (Lay-up thickness x Lay-up speed^2)*

(All the equations would be more reader friendly if typed using Math Equation editor in MS Word. Especially multiplication sign would be more easy to distinguish)

Table: 5 ANOVA results of the quadratic model (after elimination)

Source	*df*	*Sum square*	*Mean square*	*F-value*	*p-value*	*Effect*	*Percentage contribution*
Model	5	2606.92	521.38	25.49	< 0.0001	significant	90.1
A-Lay-up Thickness	1	1059.46	1059.46	51.79	< 0.0001	significant	36.61
B-Lay-up Speed	1	155.87	155.87	7.62	0.0153	significant	5.39
C-Nozzle Dia	1	794.24	794.24	38.82	< 0.0001	significant	27.45
AC	1	119.51	119.51	5.84	0.0299	significant	4.13
C^2	1	477.85	477.85	23.36	0.0003	significant	16.52
Residual	14	286.41	20.46				
Lack of Fit	9	286.40	31.82	90922.20	< 0.0001	significant	9.9
Pure Error	5	1.750E-003	3.500E-004				
Total	19	2893.33					

R^2 = 0.9010 Adjusted R^2 = 0.8657

(the last sentence of the paragraph prior to this paragraph also states the same thing – about eliminating factors and improving model. Looks like a repetition. Please retain at one place only)To fit the quadratic model appropriately the non-signification terms are eliminated by a backward elimination process. The ANOVA table for reduced quadratic model is shown in Table 5. All the factors are found to be significant. The percentage contribution of the quadratic model was 90% as also seen in figure 3. The effect of lay-up thickness contributes to about 1/3 to the output. The second most influencing factor is the nozzle diameter. The variation in lay-up speed during fabrication has very little effect on the flexural strength. The nozzle diameter and the thickness increase the surface area to enhance bonding between each layer. The sample size prepared for tests is only 127 mm, hence the lay-up speed might not have influenced due to the smaller size of the specimen.

The model is in full agreement with the data as all the value are significant, the model generated using the significant value is given in the below equation (6).

Flexural strength = 73.55 – 10.29 x Lay-up thickness – 9.95 x Lay up Speed – 8.91 x Nozzle Diameter + 3.87 x Layup Thickness x Nozzle Diameter + 9.78 x Nozzle Diameter^2 (6)

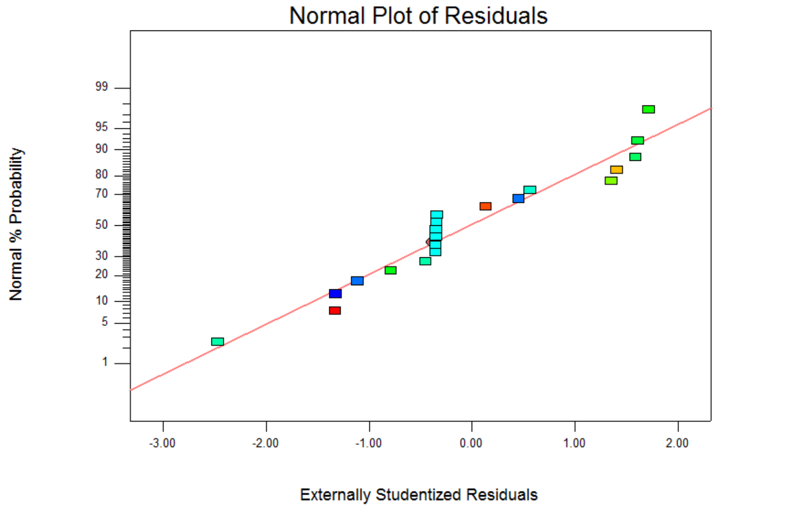

Figure: 3.Normal Probability plot of residuals at 90 % of confidence interval

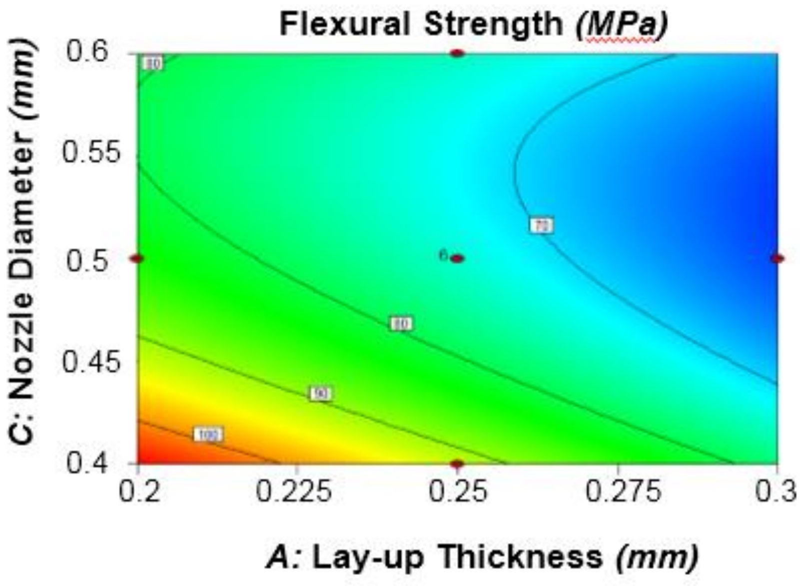

Figure: 4 Contour plot showing the effect of nozzle diameter and lay-up thickness on flexural strength

The contour plot is the 2-dimensional representation of the 3-dimensional graph. It is a topographical graphical representation of longitude, latitude, and elevation in which x-, y-, and z-values are plotted. Figure 4 presents a surface of the contour plot generated by the prediction of the flexural strength of the 3D printed sample from the examination of the response surface of the flexural strength based on the variables lay-up thickness and nozzle diameter. A 3- Dimensional response surface shown in

Figure 5, gives the important information, and depicts about the flexural strength based on the other influencing factors like lay-up thickness and nozzle diameter.

RSM is an experimental technique used to find the optimal response within specified ranges of the factors. For fitting a second-order equation for the response surface these designs are used. The quadratic equations of the model, the curvature in the true response surface function. RSM can estimate the maximum or minimum factor region exists inside it. For the industrial applications, RSM designs involve less number of factors, because the essential number of runs escalates rapidly with the number of influences.

It has been observed that the decrease in lay-up thickness and nozzle diameter has prolonged the curing time of the PLA substrate with the adjacent layer exhibiting high flexural strength. From the graph, it is seen that lay-up thicknesses up to 0.225 mm with a nozzle diameter of 0.4 mm has a flexural strength of 100 MPa and higher. It is interesting to note that there is no influence of lay-up thickness (between 0.2 to 0.275 mm) for the nozzle diameter of 0.55 mm. The flexural strength remains constant. The flexural strength is decreased as the lay-up thickness is increased for the same nozzle diameter. Hence, the decrease in the nozzle diameter is responsible for increasing flexural strength. Whilst there is a slight decrease in the flexural strength as the lay-up thickness is increased.

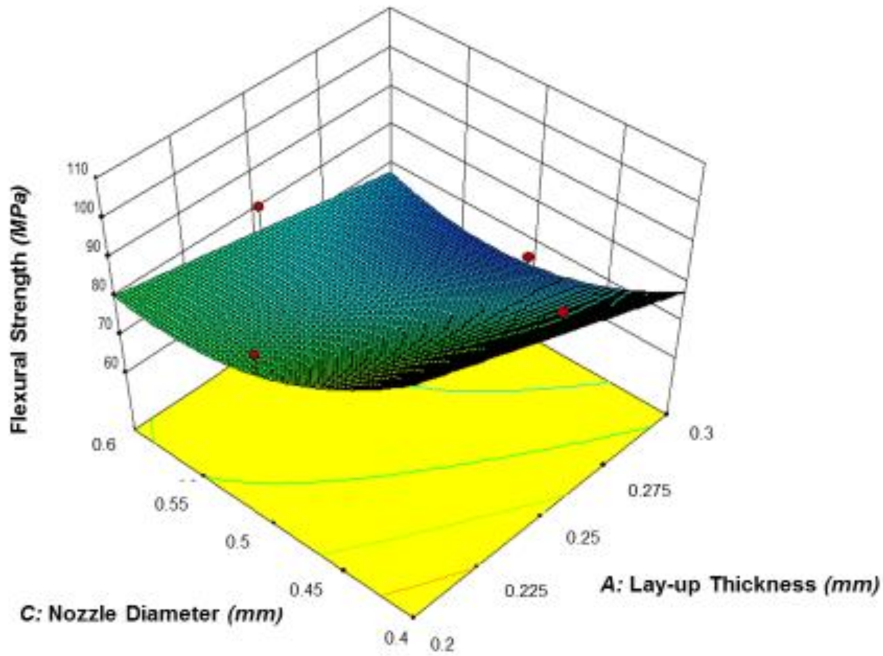

Figure 5 Response surface graph shows the effect of nozzle diameter and lay-up thickness on flexural strength

4. Conclusions

The investigation on the effect of PLA parts prepared by three different manufacturing parameters such as Lay-up thickness, Lay-up speed, and Nozzle diameter were studied in detail and its influence on the flexural strength has led to the following conclusions.

- The flexural strength was completely dependent on the manufacturing process such us lay-up thickness, Lay-up speed and nozzle diameter

- The decrease in lay-up thickness and nozzle diameter during fabrication showed improvement in flexural strength.
- The decrease in the nozzle diameter exhibited a steady increase in flexural strength.
- There is a slight decrease in the flexural strength as the lay-up thickness was increased.
- The quadratic equation has been developed to analyze the effect of the three process parameters statistically.

References

[1]. Wiedemann B, Jantzen H.A., Strategies and applications for rapid product and process development in Daimler-Benz AG. Computer in Industery 39(1):11–25,(1999).

[2]. Upcraft S, Fletcher R., The rapid prototyping technologies. Rapid Prototyping Journal 23(4):318–330, (2003).

[3]. Mansour S, Hauge SR ., Impact of rapid manufacturing on design for manufacturing for injection moulding. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 217(4) 453-461, (2003).

[4]. HopkinsonN,Hagur RJM,Dickens PH., Rapid manufacturing: an industrial revolution for the digital age. John Wiley and Sons Ltd., England (2006).

[5]. Bernarand A, Fischer A., New trends in rapid product development. CIRP Annals Manufacturing Technology, 51(2):635–652,(2002).

[6]. Levy GN, Schindel R, Kruth JP, Leuven KU, Rapid manufacturing and rapid tooling with layer manufacturing (LM) Technologies—state of the art and future perspectives. CIRP Annals Manufacturing Technology 52(2):589–609(2003).

[7]. Pilipović A, Raos P, Šercer M., Experimental analysis of properties of materials for rapid prototyping. International J Advance Manufacturing Technology 40(11–12):105–115(2009).

[8]. Standard Terminology for Additive Manufacturing Technologies. ASTM International Designation : F2792-12a (2012)

[9]. Myers RH, Montgomery DC, Response surface methodology, Wiley (2002).

[10]. Farzad Rayegani , Godfrey C. Onwubolu, Fused deposition modelling (FDM) process parameter prediction and optimization using group method for data handling (GMDH) and differential evolution (DE), International Journal of Advance Manufacturing Technology 73:509–519 (2014).

[11]. Liu Xinhua & Li Shengpeng , Liu Zhou, Zheng Xianhua, Chen Xiaohu, Wang Zhongbin , An investigation on distortion of PLA thin-plate part in the FDM process, International Journal of Advance Manufacturing Technology 79:1117–1126 (2015).

[12]. Es Said, Os Foyos J, Noorani R, Mandelson M, Marloth R, Pregger BA. Effect of layer orientation on mechanical properties of rapid prototyped samples. Mater Manuf. Process;15(1):107–122 (2000).

[13]. Ahn SH, Montero M, Odell D, Roundy S, Wright PK. Anisotropic material properties of fused deposition modelling ABS. Rapid Prototyping J,8(4):248–57, (2002).

[14]. Anitha S. Arunachalam, P.Radhakrishnan, Critical parameters influencing the quality of prototype in fused deposition modeling, Journal of materials processing technology, 118 385-388(2001)

[15]. Wang, Tian Ming, Xi Jun Tong, Jin Ye. A model research for prototype warp deformation in the FDM process. Int. J Adv. Manuf. Technology,33 (11–12) 1087–1096 (2007).