Indian Journal of Engineering & Materials Sciences
Vol. 29, February 2022, pp. 92-99

Modeling and analysis of surface roughness in fused deposition modeling based on infill patterns

Pooja Patil[a], Sunil J Raykar[b], Jaiprakash Bhamu[c], & Dharmendra Singh[d*]
[a,c,d]Government Engineering College, Bikaner, Rajasthan 334 004, India
[b]D Y Patil College of Engineering and Technology, Kolhapur, Maharastra 416 006, India

Receive: 31 January 2021; Accepted: 25 August 2021

This paper presents an approach of modeling for surface roughness of Polylactic Acid (PLA) polymer components printed with Fused Deposition Modeling (FDM) based Additive Manufacturing (AM) process. With additive manufacturing technology one can build the components of metal, polymers and variety of composites with good dimensional accuracy. FDM is one of the additive manufacturing process which is used to build products of various polymers. In this investigation PLA components are built using FDM with different Infill Patterns viz. Zigzag, Triangles and Gyroid. Based on surface roughness measurement of components, predictive mathematical models for surface roughness are generated for different infill patterns. The analysis of surface roughness based on layer thickness and infill pattern is presented. The error between predictive surface roughness and experimental surface roughness ranges between 0.1 to 9.5%. For this investigation Gyroid infill pattern shows favourable results for surface roughness. The workable ranges for process parameter under investigation are infill percentage of 70 to 90 %, layer thickness of 0.2 to 0.22 mm and printing speed of 70 to 90 mm/s.

Keywords: Additive Manufacturing (AM), Fused Deposition Modeling, Surface Roughness, Infill Patterns, Infill Percentage, printing Speed

1 Introduction

Today's customer mainly demands product of highest quality and optimum costs. To meet this demand manufacturer all around the world are taking huge efforts by using new technologies, newer processes and combination of materials. To get quality at optimum cost, the major task is to minimize the wastages in cycle of manufacturing. Additive manufacturing is one of these advanced manufacturing process which uses only optimum required material with desired dimensional accuracy. Additive manufacturing (AM) produces highly accurate components with almost no wastage of material as it builds component by adding the material layer by layer as per CAD model of component. Because of its capability to produce high quality product having intricate shapes with least wastage of material and application is found in almost every sector in the world. It can produce components of metal, polymers and composites which can be utilized in automobile, aerospace, medical, construction, and many other fields. Fused Deposition Modeling is an AM process which produces end user products and models of polymers. FDM produces parts by heated and extruded filaments through a small nozzle, the direction of which is computer controlled. The layers of the material are extruded on top of each other to create the component. The parts here are created with a 3D model that is sliced with a slicing program having number of layers, the thickness of which can be determined by the operator. The slicing program then generates a tool path to fill the layer boundaries[1, 2]. Since it generates component using a CAD model it has very high capabilities in terms of precession and accuracy also it can produce any complex shape. The 3D printing of FDM begins with the development of a 3D model of a component or part to be printed. After this, the model is translated to an STL format, which is later sliced into a number of layers by an appropriate slicing application. The parts are finally manufactured and cleaned as needed[3,4]. Support structures can often be given on overhanging parts for dimensional accuracy. Despite the potential benefits, the application of AM in the production of functional parts is still limited due to the nature and properties of the component produced. It depends on the process parameters, which have a critical effect on quality of a product in terms of dimensional accuracy apart from

*Corresponding author (E mail:dharmendra3103@gmail.com)

surface quality of printed parts. As, quality of any manufactured part is evaluated through dimensional accuracy and quality of surface generated after manufacturing. In FDM too, the two in terms of surface roughness are very important aspects to assess the quality of printed parts. The printing parameters used highly affect quality of parts. So, proper selection of process parameters is very important aspect of FDM. Larger layer thickness and faster printing speed are two main reasons of poor quality printed parts[5,6]. But to complete the part with FDM in shorter time people prefers higher printing speeds with larger layer thickness. This will surely deteriorate the quality of printed surface. According to Anitha *et al*. (2001)[7] layer thicknesses is the most deciding parameter as far as surface roughness of FDM parts is concerned. To improve surface quality, lower layer thickness must be preferred. Few studies reflects that 0˚ and 90˚ orientation angles are very effective for surface finish FDM parts with the layer thickness being second parameter to have influence on surface finish in FDM[8-10].

According to literature negative air gap may result in poor surface quality[11]. Wider raster width improves surface finish as compared to smaller raster width, since the impact of heat and high temperature on the smaller raster is more. Also sometimes a complex curved surface reduces the surface finish[12]. Build direction along with orientation of the parts and raster angle can greatly influence the surface roughness[13]. According to Alsoufi and Elsayed[14], layer height and nozzle diameter are important considerations to improve surface roughness. Several other FDM process parameters like air gap, raster angle, contour width, temperature and raster width, can also have noticeable effect on surface roughness[15].

To improve surface roughness proper selection and development of mathematical and analytical models are necessary. There are several attempts to optimize the process parameters and also to develop surface roughness models done by some researchers. Chohan *et al*. (2016)[16] formulated a mathematical model for average surface roughness of FDM parts which are further processed by vapour processing. These models are developed on basis of Taguchi and ANOVA analysis. Artificial Neural Networks technique was used for optimization of parameters like; orientation angle and layer thickness for producing complex geometries with improved accuracy[17]. Boschetto *et al*. (2013)[18] constructed a geometric model of surface roughness profile and derived relationship to anticipate several roughness parameters viz. average roughness values, root mean square roughness and peak height based on orientation angle and layer thickness. Peng *et al*. (2014)[19] proposed the use of response surface methodology combined with fuzzy inference system to optimize process parameters of FDM. They reported that this combined method of optimization can improve accuracy and efficiency of FDM process. Pramanik *et al*. (2020)[20] has developed mathematical models for surface roughness for FDM using second degree regression equations. Parameters used in their investigation were printing speed, bed temperature, infill density, extruder temperature, and layer height with Ra value as response. Sai *et al*. (2020)[21] has used Adaptive Neuro-Fuzzy Inference System (ANFIS) model and whale optimization algorithm for modeling and optimization of FDM process. Their methodology can predict optimum combination of process parameters of FDM accurately. There is scope for Optimization paradigms for surface roughness and predictive mathematical models for surface roughness for FDM. This will help FDM community to use optimum parameters and these models for printing high quality parameters. This paper presents an approach to develop mathematical models for prediction of surface roughness based on three infill patterns using responses surface models. The optimum parameters for FDM are also proposed in this investigation.

2 Materials and Methods

2.1 Printing Details

A FDM printer with build size 200 × 200×200 with nozzle of 0.4 mm diameter is used for printing the components. The components are bearing block used for building of 3D printer. These components are manufactured with Polylactic Acid (PLA) filament of 1.75 mm diameter. The dimensions and 3D model of component is shown in Fig. 1. For slicing, the model Ultimaker Cura is used.

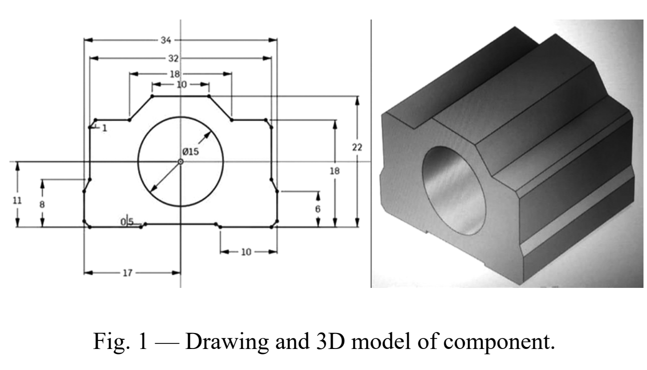

Fig. 1 — Drawing and 3D model of component.

2.2 Process Parameters and Design of Experiments

For this investigation infill pattern, layer thickness, infill % and printing speed are selected as process parameters. The main focus of the investigation is infill pattern. The predictive mathematical models are prepared on basis of infill patterns. Gyroid, ZigZag and Triangles are the patterns considered for the investigation. The detailed process parameters with their levels are shown in Table 1. Other than the process parameters mentioned some important parameters while printing are nozzle temperature (210˚ C), built plate temperature (60˚ C). Whereas, cooling is 100% and built plate adhesion is skirt. For experimental design L_{27} (3^13) Taguchi based array is used, each process parameter is assigned with one column in the array. Row one is assigned for infill pattern, two is assigned for infill %. Row three is assigned for printing speed and four is assigned for layer thickness. The details of array are shown in Table 2.

2.3 Measurement of Surface Roughness

Surface roughness measurement for the component is carried out after cleaning. For measurement of surface roughness a Mitutoyo make SJ 210 portable roughness tester is used. Surface roughness Ra parameter is considered for assessment of surface quality. During measurement ISO 1997 standard is followed with cut off length of 0.8 mm, probe speed of 0.5 mm/sec and 5 intervals of cut off length are selected for measurement of roughness. Roughness is measured at three points and at every point three readings are taken, therefore the surface roughness value indicates average of all nine readings as a Ra value. Figure 2 shows set up for surface roughness measurement.

2.4 Predictive Mathematical Models using Responses Surface Models (RSM)

Response surface predictive models can be used to develop relationship between process parameters (input variables) and responses (output variables). These models also can develop relationship on basic of interaction of input variables. First order and second order models can be developed based on requirement of analysis. When interaction of various

Table 1 — Process parameters and their levels

Parameter	Level 1	Level 2	Level 3
Infill Pattern	ZigZag	Triangles	Gyroid
Infill %	70	80	90
Printing Speed	60	80	100
Layer Thickness	0.2	0.25	0.3

Table 2 — Process parameters and measured responses

Exp. No	Infill Pattern	Infill %	Printing Speed	Layer Thickness	Predicted Ra with Model	Experimental Ra	% Error
1	ZigZag	70	60	0.2	13.1686	13.4285	1.94
2	ZigZag	70	80	0.25	21.4737	20.565	4.42
3	ZigZag	70	100	0.3	25.0623	25.919	3.31
4	ZigZag	80	60	0.3	23.2311	23.189	0.18
5	ZigZag	80	80	0.2	12.7978	12.81	0.1
6	ZigZag	80	100	0.25	22.2168	21.831	1.77
7	ZigZag	90	60	0.25	19.6712	20.09	2.08
8	ZigZag	90	80	0.3	25.4578	25.081	1.5
9	ZigZag	90	100	0.2	13.4602	13.626	1.22
10	Triangles	70	60	0.2	13.1341	13.062	0.55
11	Triangles	70	80	0.25	21.4323	21.295	0.64
12	Triangles	70	100	0.3	25.0139	25.957	3.63
13	Triangles	80	60	0.3	24.0672	23.195	3.76
14	Triangles	80	80	0.2	12.3442	12.595	1.99
15	Triangles	80	100	0.25	21.7561	20.91	4.05
16	Triangles	90	60	0.25	20.0951	20.998	4.3
17	Triangles	90	80	0.3	25.8747	25.844	0.12
18	Triangles	90	100	0.2	12.5874	12.449	1.11
19	Gyroid	70	60	0.2	13.8547	13.667	1.37
20	Gyroid	70	80	0.25	19.801	20.847	5.02
21	Gyroid	70	100	0.3	21.0308	19.231	9.36
22	Gyroid	80	60	0.3	22.8448	23.759	3.85
23	Gyroid	80	80	0.2	12.756	12.493	2.11
24	Gyroid	80	100	0.25	19.8161	21.048	5.85
25	Gyroid	90	60	0.25	20.9157	19.594	6.75
26	Gyroid	90	80	0.3	24.3435	24.751	1.65
27	Gyroid	90	100	0.2	12.6904	12.663	0.22

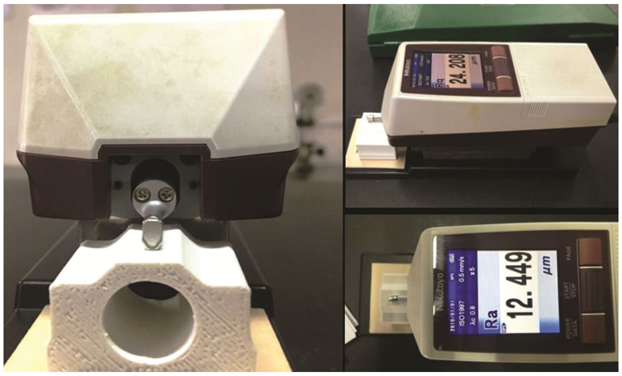

Fig. 2 — Surface roughness measurement.

process parameters is desired, second order models are used. In this analysis second order polynomial model is used to develop relationship between surface roughness and process parameters of FDM. The main focus of this analysis is infill patterns therefore three such models are developed based of three infill patterns and surface roughness for these infill patterns. These models gives relationship between surface roughness Ra for ZigZag, Triangles , Gyroid patterns and process parameters infill %, layer thickness, printing speed. Since the model is second order model interactions between these process parameters are also considered. Minitab statistical software is used to generate these predictive models. Based on response surface modeling the predictive models generated are:

Surface roughness for Zigzag pattern

$$Ra = -8.9 - 1.030\ \mathrm{IP} - 0.025\ \mathrm{PS} + 446\ \mathrm{LT} + 0.00300\ \mathrm{IP} \times \mathrm{IP} + 0.00001\ \mathrm{PS} \times \mathrm{P} - 945\ \mathrm{LT} \times \mathrm{LT} + 0.00106\ \mathrm{IP} \times \mathrm{PS} + 1.79\ \mathrm{IP} \times \mathrm{LT} \quad \ldots (1)$$

Surface roughness for Triangles pattern

$$Ra = -9.4 - 1.029\ \mathrm{IP} - 0.047\ \mathrm{PS} + 455\ \mathrm{LT} + 0.00300\ \mathrm{IP} \times \mathrm{IP} + 0.00001\ \mathrm{PS} \times \mathrm{P} - 945\ \mathrm{LT} \times \mathrm{LT} + 0.00106\ \mathrm{IP} \times \mathrm{PS} + 1.79\ \mathrm{IP} \times \mathrm{LT} \quad \ldots (2)$$

Surface roughness for Gyroid pattern

$$Ra = -5.3 - 0.957\ \mathrm{IP} - 0.098\ \mathrm{PS} + 428\ \mathrm{LT} + 0.00300\ \mathrm{IP} \times \mathrm{IP} + 0.00001\ \mathrm{PS} \times \mathrm{P} - 945\ \mathrm{LT} \times \mathrm{LT} + 0.00106\ \mathrm{IP} \times \mathrm{PS} + 1.79\ \mathrm{IP} \times \mathrm{LT} \quad \ldots (3)$$

After generating mathematical predictive models the predicted surface roughness values from above models are calculated. These predicted values are then compared with actual values with time series plots shown Figs (3-5). The errors related to predictive models with respect to actual surface roughness are calculated. These predicted values along with respective errors are shown in Table 2. ANOVA for

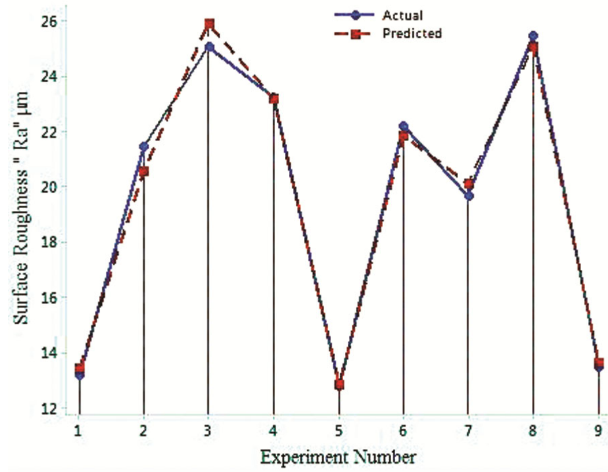

Fig. 3 — Comparison of actual and predicted surface roughness for Zigzag pattern.

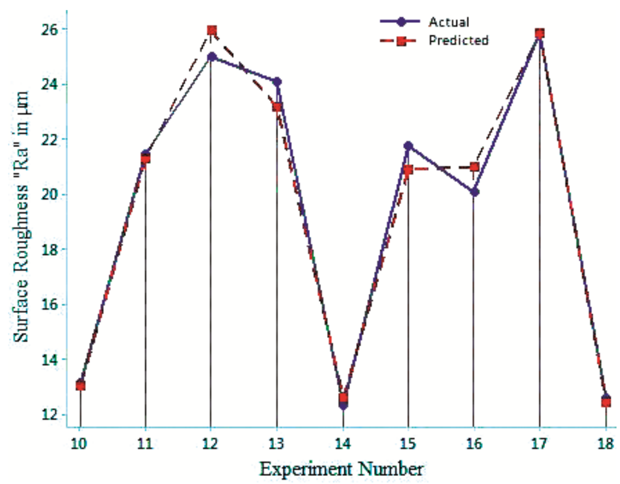

Fig. 4 — Comparison of actual and predicted surface roughness for Triangles pattern.

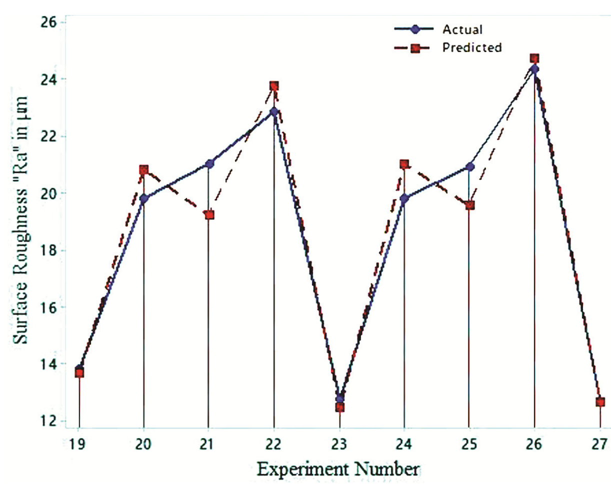

Fig. 5 — Comparison of actual and predicted surface roughness for Gyroid pattern.

model is also done to see significance of parameters and their interactions on surface roughness. This is performed at 95% confidence level. Significance of process parameters on surface roughness is determined on basic of p value in ANOVA Table 3. P value gives important information about relationship between process parameter and response. At 95 % confidence level parameters to have significance effect on surface roughness p value must be less than 0.05. R-sq values are shown below; ANOVA table can be used to predict effectiveness of models.

3 Results and Discussions

The predicted values of surface roughness Ra from mathematical models generated using RSM finds a very close match with actual values of surface roughness. This can be seen from Figs (3-5) and Table 2 that for all the infill patterns viz. ZigZag, Triangles and Gyroid the errors between actual and predicted values are very low. The lowest average % error between actual and predicted values is for 1.84 % which is for ZigZag pattern. The highest average % error between actual and predicted values is for 4.02 % which is for Gyroid pattern and for Triangles the average % error is 2.24 %. For all the experiments conducted the average % error varies between 0.1 % to 9.36 % which are less than even 10 %. The smallest % error is 0.1 % which is for ZigZag pattern, 80 % infill, 80 mm/sec speed and 0.2 mm layer thickness. The largest error is 9.36 % which is for Gyroid pattern, 70 % infill, 100 mm/ sec speed and 0.3 mm layer thickness. To see variation in surface roughness for process parameters under investigation main effect plots for data is drawn. Main effects plot is shown in Fig. 6. It can be seen in main effect plot that with Gyroid pattern a considerable improvement in surface roughness is observed. Average surface roughness found at Gyroid pattern is 18.6726 µm, ZigZag pattern is 19.6155 µm and Triangles pattern is 19.5894 µm.

Table 3 — ANOVA for process parameters and their interactions

Source	DF	Adj SS	Adj MS	F-Value	p-Value
Model	16	615.480	38.468	27.25	0.000
Linear	5	333.267	66.653	47.22	0.000
Infill %	1	0.070	0.070	0.05	0.828
Printing Speed	1	3.172	3.172	2.25	0.165
Layer Thickness	1	289.190	289.190	204.86	0.000
Infill Pattern	2	5.192	2.596	1.84	0.209
Square	3	26.085	8.695	6.16	0.012
Infill %*Infill %	1	0.542	0.542	0.38	0.550
Printing Speed* Printing Speed	1	0.000	0.000	0.00	0.993
Layer Thickness* Layer Thickness	1	25.131	25.131	17.80	0.002
2-Way Interaction	8	20.509	2.564	1.82	0.186
Infill %*Printing Speed	1	0.201	0.201	0.14	0.714
Infill %*Layer Thickness	1	3.586	3.586	2.54	0.142
Infill %*Infill Pattern	2	2.086	1.043	0.74	0.502
Printing Speed* Infill Pattern	2	6.722	3.361	2.38	0.143
Layer Thickness* Infill Pattern	2	5.520	2.760	1.96	0.192
Error	10	14.116	1.412		
Total	26	629.597			

R-sq 97.76 %

A Gyroid pattern gives good results for surface roughness. While printing with Gyroid patterns improvement of 5.04 % as compared to ZigZag and 4.90 % as compared to Triangles is observed. The Gyroid pattern is considered as high strength infill pattern whereas Triangles is medium strength and ZigZag is low strength infill pattern [22]. ZigZag pattern generates lines with layers.

A triangles pattern is a mesh of triangles whereas Gyroid generates wave like structures. This is visible in Fig. 7. Components in Fig.7 are generated with interrupted FDM process to see internal structure of these three infill patterns. A Gyroid structure is more closely packed with filament material. Since it is 3D

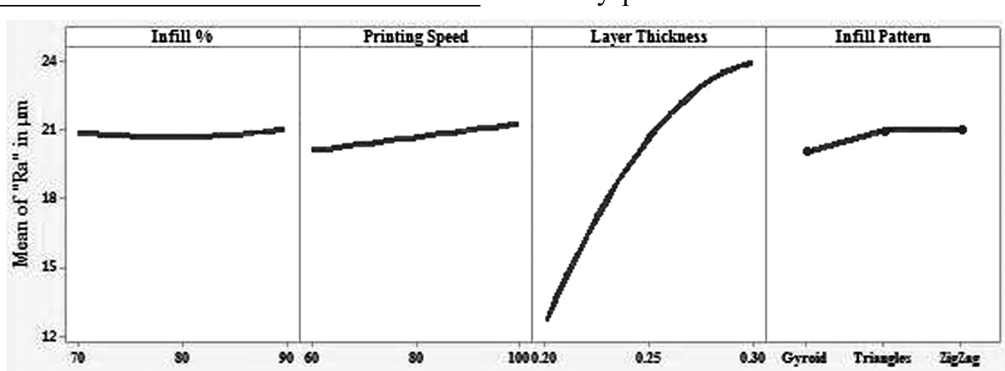

Fig. 6 — Main effect plot for surface roughness.

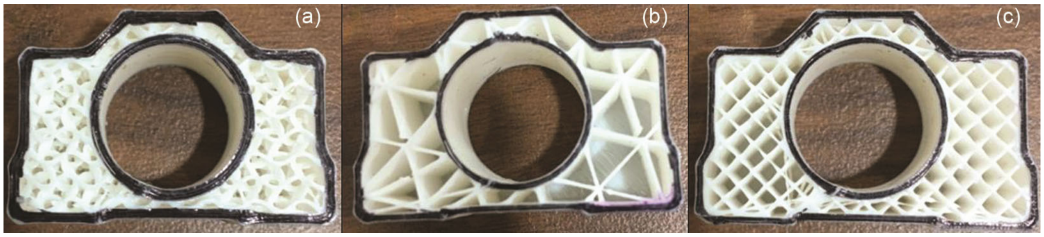

Fig. 7 — Infill patterns used in investigation; (Zigzag), (b) Triangles, and (c) Gyroid.

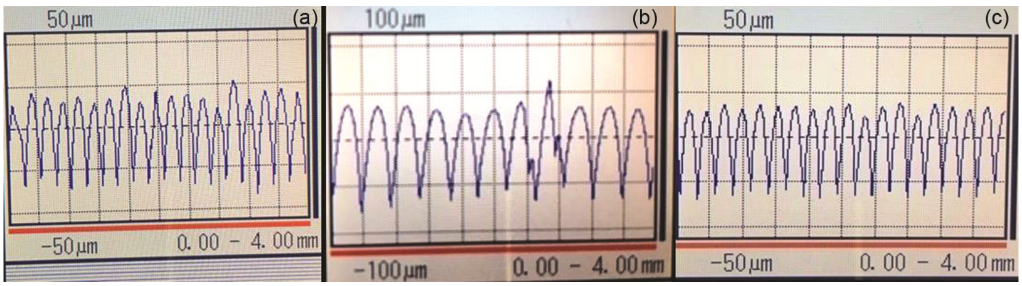

Fig. 8 — Surface roughness profiles at infill % 70, printing speed 60, Layer Thickness (a) ZigZag; (b) Triangles, and (c) Gyroid.

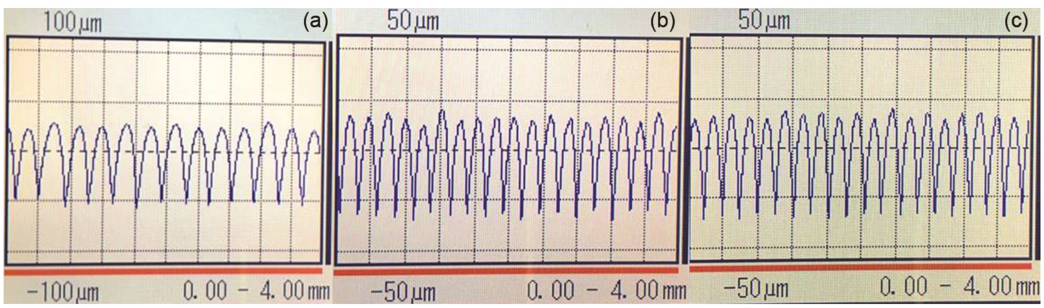

Fig. 9 — Surface roughness profiles at infill % 90, printing speed 60, layer thickness 0.25 (a) ZigZag, (b) Triangles, and (c) Gyroid.

pattern the surface generated is also smoother with less irregularities as compared to other two patterns. The surface patterns generated with these three patterns for Infill % 70, Printing Speed 60, Layer Thickness 0.2 are shown in Fig. 8 and that at Infill % 90, Printing Speed 60, Layer Thickness 0.25 are shown in Fig. 9.

These figures clearly show that the surface roughness profiles for Gyroid is more regular as compared to both ZigZag and Triangles pattern. Even pitch of profile for Gyroid is very less as compared to other two patterns. The successive peaks and valleys in Gyriod are very closely spaced for almost all the process parameter profiles used in investigation which results in improvement of surface roughness for Gyroid as compared to other two infill patterns.

ANOVA Table 3 suggests that Layer thickness is the most influential parameter for surface. It affects surface roughness at 95% confidence level. A layer thickness goes on increasing from 0.2 to 0.25 and further from 0.25 to 0.3 mm surface roughness also increases. The mean surface roughness found at 0.2 mm layer thickness is 12.9771 µm, at 0.25 mm layer thickness is 20.7976 µm and 0.3 layer thickness is 24.1019 µm. So an average improvement of 60% as compared to 0.25 mm layer thickness and 85 % as compared 0.3 mm layer thickness is found at 0.2 mm layer thickness. For smaller layer thickness, material is very closely stacked which is very obvious as far as FDM is concerned. This results in less material irregularities for printed components. The rise in surface roughness with increase in layer thickness is clearly visible in main effect plot. The second parameter which has influence on surface finish after layer thickness is Infill pattern. Though infill pattern do have significance at 95% confidence level but it shows some influence on surface roughness which is already previously discussed in this section. Printing speed and infill % do not have any significant trend for surface roughness. The interactions between process parameters also do not show significant effect at 95% confidence level on surface roughness which can be clearly seen from ANOVA Table 3. To find out workable range for surface roughness for continuous variables in this investigation which are printing speed, infill % and layer thickness contour plots are drawn for surface roughness based on these variables. These plots are shown in Figs (10-12).

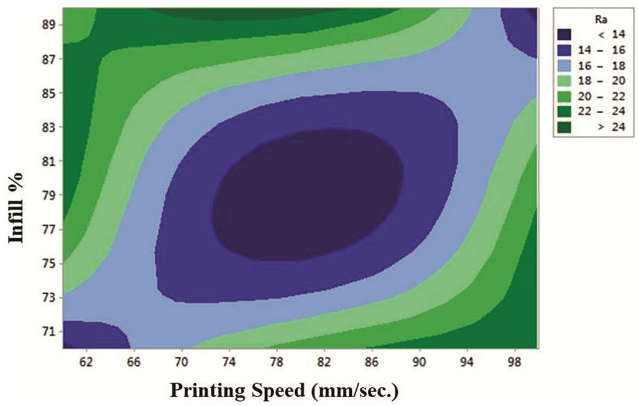

Fig. 10 — Contour plot of Ra for infill % vs printing speed.

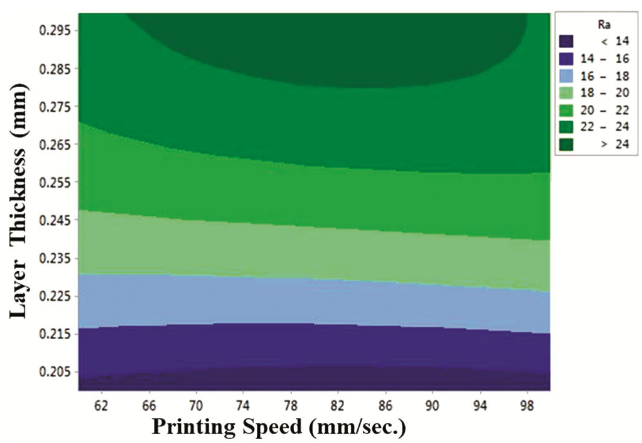

Fig. 11 — Contour plot of Ra for layer thickness vs printing speed.

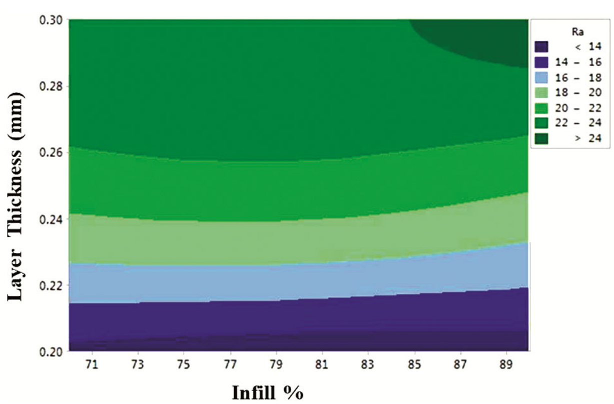

Fig. 12 — Contour plot of Ra for layer thickness vs infill %.

From contour plots workable range of process parameters for better results of surface roughness can be identified. From Figs (10-12) the workable range for printing speed, layer thickness and infill % can be predicted.

From the surface roughness values measure after printing that are shown in Table 2, the smaller values for surface finish are less than 14 µm, and the range for contour plot for surface roughness is fixed as 14-16 µm, 16-18 µm, 18-20 µm, 20-22 µm and larger values above 24. So the working range of surface roughness for parameter under investigation can be identified is less than 14 µm and between 14 -18 µm which are in faint and dark blue colour, from faint green to dark colour the surface roughness range is 18-24 µm and more than 24 µm. With this the workable ranges of process parameters identified from contour plots are infill % of 70 % to 90 %, layer thickness of 0.2 mm to 0.22 mm and printing speed of 70 mm/s to 90 mm/s. From main effect plot, it can be seen that optimum parameter setting for present investigations is for Gyroid pattern which is 80 % infill, 60 mm/ sec printing speed and 0.2 mm layer thickness.

4 Conclusion

Modeling and analysis of surface roughness of Polylactic Acid (PLA) polymer components printed with FDM is based on infill patern and other three process parameters viz. Infill %, layer thickness, printing speed is presented. RSM based predictive mathematical models are generated for surface roughness value Ra. The analysis is carried out based on ANOVA, main effect plots and contour plots. Following are some important conclusions this investigation. All these conclusions are based on process parameters under investigation.

- Predicted mathematical models shows good fitment with experimental values of surface roughness. For all models generated % error varies between 0.1 to 9.36 % so, these models can be conveniently used for prediction of surface roughness within the range of process parameters.
- Gyroid pattern shows favourable results for surface roughness. Average surface roughness found at Gyroid pattern is 18.6726 µm, Zigzag pattern is 19.6155 µm and Triangles pattern is 19.5894 µm.
- Layer thickness is the most influencing parameter for surface. It affects surface roughness at 95%

confidence level. The second parameter which has influence on surface finish after layer thickness is Infill pattern.

- The workable ranges of process parameters identified from contour plots are infill % of 70 to 90 %, layer thickness of 0.2 mm to 0.22 mm and printing speed of 70 to 90 mm/s.

References

1 Alafaghani A & Qattawi A, *J Manuf Proc*, 36 (2018) 164.

2 Reddy V, Flys O, Chaparala A, Berrimi C E, Amogh V, & Rosen B G, *Proced Manuf ,* 25 (2018) 389.

3 Raykar S J & D'Addona D M, *Mater Today: Proceed*, 27-1 (2020) 344.

4 Raykar S J , Narke M M, Desai S B, & Warke S S, *Proceedings of the 2nd International Conference on Advanced Technologies for Societal Applications-Techmosocietal* (Springer Cham), (2020) 771.

5 Liu Z, Wang Y, & Wu B, *Int J Adv Manuf Tech*, 102 (2019) 2877.

6 Vaezi M, & Chua C K, *Int J Adv Manuf Technol*, 53 (2011): 275.

7 Anitha R, Arunachalam S, & Radhakrishnan P, *J Mater Process Tech,* 118 (2001), 385.

8 Vasudevarao B, Natarajan D P, Henderson M, & Razdan A, In *Proceedings of the Solid Freeform Fabrication Proceedings, Austin, TX, USA, 7-9 August* (2000) 251.

9 Byun H S, & Lee K H, *Robot and Comp Integ Manuf*, 22 (2006) 69.

10 Noriega A, Blanco D, Alvarez B J, & Garcia A, *Int J Adv Manuf Tech,* 69 (2013) 2301.

11 Galantucci L M, Lavecchia F, & Percoco G, *CIRP Ann,* 58 (2009) 189.

12 Bakar N S A, Alkahari M R, & Boejang H *J, Zhejiang Univ Sci A* 11(2010) 972.

13 Durgun I, & Ertan R, *Rapid Prot Jour*, 20-3 (2014) 228.

14 Alsoufi M S, & Elsayed A E, *Amer J Mech and Eng*, 5 (2017) 211.

15 Chohan J S, & Singh R, *Rapid Prot Jour*, 3 (2017), 495.

16 Chohan J, Singh R, & Boparai K, *J Manuf Proc*, 24 (2016) 161.

17 Boschetto A, Giordano V, & Veniali F, *Int J Adv Manuf Tech*, 27 (2013) 27.

18 Boschetto A, Giordano V, & Veniali F, *Rapid Prot J,* 19(4) (2013) 240.

19 Peng A, Xiao X, & Yue R, *Int J Adv Manuf Technol*, 73 (2014) 87.

20 Pramanik D, Mandal A, & Kuar A S, *Mater Today Proc*, 26-20 (2020) 860.

21 Sai T, Pathak V K ,& Srivastava A K, *J Braz Soc Mech Sci and Engineering* , 42 (2020) 617.

22 https://all3dp.com/2/cura-infill-patterns-all-you -need-to-know/ A.O -1/1/2021, 11.30 am IST.