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

Analysis of Fused Deposition Modeling Process for Additive Manufacturing of Abs Parts

B. Doloi*, S. Kumar, N. Maity, G. Sen
Production Engineering Department, Jadavpur University,
Kolkata -700 032

Abstract

Fused deposition modeling (FDM) is the popular additive manufacturing process for fabricating complex parts. In comparison with traditional manufacturing, it can rapidly fabricate prototypes with complex shapes using thermoplastic, such as acrylonitrile butadiene styrene (ABS), polyethylene, polypropylene, polycarbonate and polylactic acid (PLA) etc. The primary characteristics of this technology consist of low cost, toxic free materials, rapid response to the need of market and high utilization rate of raw materials. Hence, this FDM technology has been widely applied in various fields such as automotive, biomedical and customer product industry. ABS is comparatively high strength material well suitable for the medical, pharmaceutical and food packaging industries etc. Parts manufactured with ABS material are biocompatible with excellent mechanical properties that are well suited for conceptual modeling, functional prototyping, manufacturing tools, and end-use-parts. In this present work 3D CAD model has been created and then the parts with various geometrical features are fabricated by FDM using ABS material. The current research includes the development of empirical relationship between the process parameters and geometrical characteristics such as circularity error and diametrical deviation of fabricated parts and also the prediction of the quality characteristics of resulting parts. This paper also includes the influence of FDM process parameters on the circularity error and diametrical deviation of cylindrical parts. The optimization results for minimum circularity error and diametrical deviation by FDM process have also been discussed in this present paper.

Keywords: Fused deposition modeling (FDM), Acrylonitrile butadiene styrene (ABS), Circularity error, Diametrical deviation.

1. INTRODUCTION

Many factors lead to modify the way the products are being designed and exploited for sustenance of organization in a competitive environment. Among them the introduction of new materials, technologies for reducing design and manufacturing lead time, services and the attention paid to the end user requirements are critical to gain advantage over competitors. The emphasis on reduction of product development time and lead time has a influence on manufacturing processes and resulted in the birth of a new generation of production equipment which manufacture part directly from the CAD (computer aided design) model on a layer by layer deposition principle without tools, dies, fixtures and human intervention. The method of such additive part generation processes is known as "Rapid Prototyping (RP)". It enables quick and easy transition from concept generation in the form of computer images to the fabrication of physical models. FDM is one of the RP technology but unlike other RP systems which involve laser, powders, resins, this FDM process uses heated thermoplastic filaments which are extruded from the tip of nozzle in a temperature controlled environment. For this there is a material deposition subsystem known as head which consist of two liquefier tips. One tip for model material and other tip for support material deposition, both of which work alternatively.
Acrylonitrile Butadiene Styrene (ABS) chemical formula ($C_8H_8 . C_4H_6 . C_3H_3N)_n$ is a common thermoplastic polymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. FDM on ABS material will be useful in the area of aerospace, medical and manufacturing industry etc.

Sood et al. [1] studied the effect of orientation, layer thickness, taguchi method on dimensional accuracy. Significant factors and their interaction are found out using taguchi method. The optimum settings of the parameters are found out so that all the three dimensions show minimum deviation from actual value settings simultaneously and the common factor settings needs to be explored. Senthilkumaran et al. [2] observed the effect of beam offset, inertia of scanning mirror and positioning errors in hatch generations, exposure strategies and part orientation on the accuracy of the part produced by SLS. Anitha et al. [3] used taguchi method to determine the influence of road width, layer thickness and speed of deposition at three different levels on surface roughness of part produced by FDM. From the results it was found that layer thickness is the most influencing factor greatly affecting surface roughness followed by raster width and speed of deposition. Hur and Lee [4] determined the slicing accuracy based on the user defined cusp height. Cusp height is the maximum deviation from layered part to the CAD surface measured in the direction normal to CAD surface. Part is sliced in different orientation in which total number of layers is minimum. Single value of cusp height for entire part is suitable for simple part geometry. The complex shape part may not have uniform cusp height requirement everywhere. Some faces of the part are required to be smooth while other faces are relatively unimportant. To overcome this limitation, slicing using non-uniform cusp height was proposed. In this approach, user specifies different allowable cusp heights for different surfaces according to their importance; a small allowable cusp height for important faces that are required to be smooth and a larger one for the other relatively unimportant faces. Khan et al. [5] concluded that layer thickness, raster angle and air gap have significantly effect on elastic properties of ABS prototype produced by FDM process. Cao and Miyamoto [6] used a direct slicing approach from Auto CAD solid models to meet the requirement of faster and precise slicing in RP.

The current research investigates the relationship between the variable parameters settings and output part quality characteristics. In order to predict the quality characteristics of resulting part and find the influences of FDM process

*Email: bdoloionline@rediffmail.com

ISBN: 978-93-80689-28-9

parameters such as layer thickness, printing speed, bed temperature, extruder temperature and fill density. The optimization for minimum circularity error and diametrical deviation of fabricated parts of ABS material by FDM process has been also discussed in this paper**.**

2. EXPERIMENTAL SETUP

FDM uses heated thermoplastic filaments which are extruded from the tip of nozzle in a temperature controlled environment. For this there is a material deposition subsystem known as head which consist of two liquefier tips. One tip for build up material and other is for deposition of material for making of parts. The material is supplied to the head in the form of a flexible strand of solid material from a supply source (reel). One pair of pulleys or rollers is utilized as material advance mechanism to grip a flexible strand of modeling material and advance it into a heated dispensing or liquefier head. The material is heated above its solidification temperature by a heater on the dispensing head and extruded in a semi molten state on a previously deposited layer of material onto the build platform following the designed tool path. The head is attached to the carriage that moves along the X-Y plane. The build platform moves along the Z direction. The drive motion are provided to selectively move the build platform and dispensing head relative to each other in a predetermined pattern through drive signals input to the drive motors from CAD/CAM system. The fabricated part takes the form of a laminate composite with vertically stacked layers, each of which consists of contiguous material fibers or raster's with interstitial voids. Fiber-to-fiber bonding within and between layers occurs by a thermally driven diffusion bonding process during solidification of the semi-liquid extruded material. Computer software CURA is used to generate STL file by slicing the CAD model. The programme has been generated as per the STL file. The programme is fed to FDM machine for movement of nozzle and deposition of material layer by layer in build platform to manufacture the parts as per CAD model. Fig. 1 shows the photographic view of FDM set up.

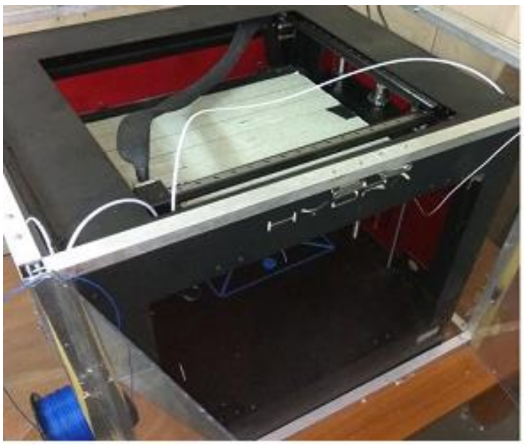

Fig. 1 Photographic view of FDM set up

3. EXPERIMENTAL PLANNING

Numbers of experiments run have been performed to select the settings or levels of the involved process parameters in this study. In instance, five levels of layer thickness have been selected according to the cost and time of building the experiment parts. FDM process parameters and their levels are given in table 1 .In this study, central composite design experiments for five levels and five factors has been made for planning of experiment. Experiments have been performed according to the plan. Coordinated Measuring Machine (CMM) and Profile Projector have been used to measure the responses such as diametrical deviation and circularity error of the fabricated parts.

Table 1 FDM process parameters and their levels.

Variable parameter	Level 1	Level 2	Level 3	Level 4	Level 5
Layer thickness (A), mm	0.1	0.11	0.12	0.13	0.14
Bed temperature (B), ^{0}C	105	110	115	120	125
Extruder temperature (C),^{0}C	231	234	237	240	243
Fill density(D), %	10	15	20	25	30
Printing speed (E), mm/s	21	22	23	24	25

4. RESULTS AND DISCUSSION

The experiments on parametric optimization of FDM of ABS material have been performed based on response surface methodology. Using the experimental results the empirical models have been developed to establish the relationship between the responses such as diametrical deviation and circularity error and the FDM process parameters. The developed models are tested by analysis of variance. The parametric influences on the responses are analyzed through response plots. The multi objective optimization of responses has been performed to find the optimal FDM parameters for achieving minimum diametrical deviation and circularity error on ABS.

General second order polynomial response surface equation, which is considered to analyze the parametric influences on the various response criteria, is given as follows:

$$\eta = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{ij} x_j^2 + \sum_{i<1} \sum_{j=2}^{k} \beta_{jj} x_i x_j \quad \text{......Eq (1)}$$

In the equation (1) η is the corresponding response. X_j are coded values of the i_{th} process parameters. The terms β_0, β_j, β_{ij} and β_{jj} are the regression coefficients. The range of each process parameters have been selected based on the results of pilot experiments. With those pilot experiments the process parameters was identified as layer thickness, bed temperature, extruder temperature, fill density, speed. In this experimentation five factors with five levels were considered.

The developed empirical model corresponding to diametrical deviation (DD) for solid cylinder is given as:

$$DD = 1310.8 - 714\ A - 0.310\ B - 11.300\ C + 1.116\ D + 6.81\ E + 1466\ A*A + 0.000247\ B*B + 0.02420\ C*C + 0.008430\ D*D - 0.0263\ E*E - 2.738\ A*B + 3.338\ A*C + 0.467\ A*D - 5.72\ A*E + 0.00151\ B*C + 0.001422\ B*D + 0.00894\ B*E - 0.00798\ C*D - 0.02580\ C*E + 0.00950\ D*E \ldots\ldots \text{Eq (2)}$$

The developed empirical model corresponding to circularity error (CE) for solid cylinder is given as:

$$CE = -14.22 - 39.03\ A + 0.06188\ B + 0.1718\ C + 0.05695\ D - 0.6891\ E + 34.08\ A*A + 0.000230\ B*B - 0.000289\ C*C + 0.000085\ D*D + 0.002670\ E*E + 0.1903\ A*B - 0.1248\ A*C + 0.1178\ A*D + 1.5644\ A*E - 0.000488\ B*C - 0.000326\ B*D - 0.000666\ B*E - 0.000248\ C*D + 0.001829\ C*E + 0.000944\ D*E \ldots\ldots \text{Eq (3)}$$

Table 2 represents the results of analysis-of-variance for diametrical deviation. The p-value for layer thickness and bed temperature are less than 0.05. The F-value of the lack of-fit is 0.2 which is less than the tabulated value. So, this two process parameters are the most significant process parameters for diametrical deviation.

Table 2 Results of ANOVA for Diametrical Deviation

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value
Model	20	4.22915	0.21146	48.92
Linear	5	0.25235	0.05047	11.68
A	1	0.17781	0.17781	41.14
B	1	0.04945	0.04945	11.44
C	1	0.01792	0.01792	4.15
D	1	0.00004	0.00004	0.01
E	1	0.00713	0.00713	1.65
Square	5	3.03409	0.60682	140.39
A*A	1	0.63007	0.63007	145.77
B*B	1	0.00112	0.00112	0.26
C*C	1	1.39144	1.39144	321.92
D*D	1	1.30297	1.30297	301.46
E*E	1	0.02031	0.02031	4.70
2-Way Interaction	10	0.94270	0.09427	21.81
A*B	1	0.29981	0.29981	69.36
A*C	1	0.16044	0.16044	37.12
A*D	1	0.00874	0.00874	2.02
A*E	1	0.05228	0.05228	12.10
B*C	1	0.00815	0.00815	1.89
B*D	1	0.02021	0.02021	4.68
B*E	1	0.03193	0.03193	7.39
C*D	1	0.22920	0.22920	53.03
C*E	1	0.09585	0.09585	22.18
D*E	1	0.03608	0.03608	8.35
Error	11	0.04754	0.00432	
Lack-of-Fit	6	0.00903	0.00151	0.20
Pure Error	5	0.03851	0.00770	
Total	31	4.27669		

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0657439	98.09%	96.07%	93.28%

Table 3 represents the results of analysis-of-variance for circularity error. The p-value layer thickness, extruded temperature and print speed are less than 0.05. The F-value of the lack-of-fit is 1.97 which is less than the tabulated value. So, this three process parameters are the most significant process parameters for circularity error.

Table 3 Result of ANOVA for circularity error

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	20	0.011482	0.000574	124.89	0.000
Linear	5	0.000417	0.000083	18.13	0.000
A	1	0.000114	0.000114	24.90	0.000
B	1	0.000012	0.000012	2.70	0.128
C	1	0.000088	0.000088	19.11	0.001
D	1	0.000010	0.000010	2.15	0.170
E	1	0.000192	0.000192	41.80	0.000
Square	5	0.001762	0.000352	76.68	0.000
A*A	1	0.000341	0.000341	74.11	0.000
B*B	1	0.000971	0.000971	211.19	0.000
C*C	1	0.000199	0.000199	43.30	0.000
D*D	1	0.000132	0.000132	28.69	0.000
E*E	1	0.000209	0.000209	45.50	0.000
2-Way Interaction	10	0.009303	0.000930	202.38	0.000
A*B	1	0.001448	0.001448	315.01	0.000
A*C	1	0.000224	0.000224	48.80	0.000
A*D	1	0.000555	0.000555	120.68	0.000
A*E	1	0.003916	0.003916	851.91	0.000
B*C	1	0.000857	0.000857	186.48	0.000
B*D	1	0.001066	0.001066	231.88	0.000
B*E	1	0.000177	0.000177	38.61	0.000
C*D	1	0.000221	0.000221	48.15	0.000
C*E	1	0.000482	0.000482	104.79	0.000
D*E	1	0.000356	0.000356	77.53	0.000
Error	11	0.000051	0.000005		
Lack-of-Fit	6	0.000036	0.000006	1.97	0.238
Pure Error	5	0.000015	0.000003		
Total	31	0.011532			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0021440	99.56%	98.76%	91.85%

Fig 2 shows the influences of layer thickness and bed temperature on diametric deviation. From the response graph, it is observed that lower value of diametric deviation has been observed at low value of bed temperature and moderate layer thickness.

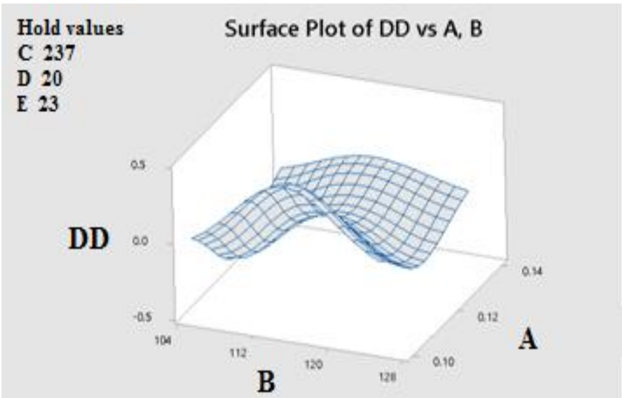

Fig. 2 Influences of layer thickness (A) and bed temperature (B) on diametrical deviation (DD)

Fig 3 shows the influences of layer thickness and speed on CE. From the response graph, it is observed that minimum value of circularity error has been obtained at high speed and lower value of layer thickness.

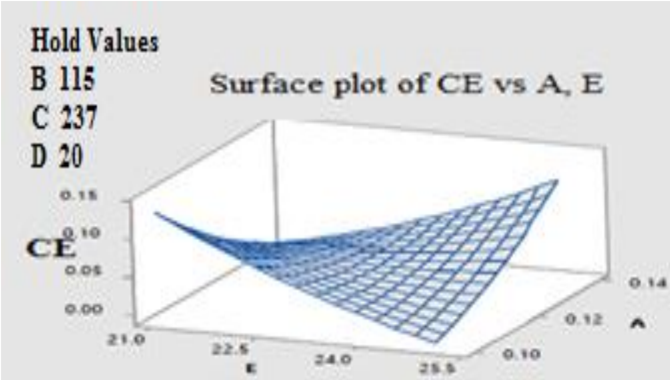

Fig.3 Influences of layer thickness (A) and speed (E) on circularity error (CE)

Fig 4 shows the influences of fill density and extruder temperature on CE. From the response graph, it is observed that lower value of circularity error has been obtained at lower value of extruder temperature and moderate value of fill density.

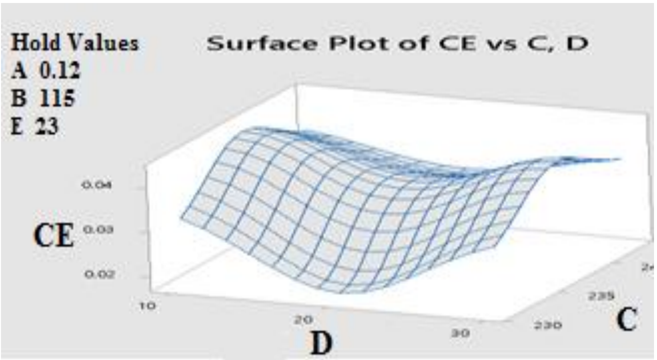

Fig. 4 Influences of extruder temperature (C) and fill density (D) on circularity error (CE)

The multi-objective optimization was performed to obtain optimal setting of process parameters to get minimum diametric deviation and circularity error of solid cylinder. The optimal values of parameters are obtain as , layer thickness of 0.1008 mm, bed temperature of 105^0 C, extruder temperature 242.9^0 C, fill density of 29%, print speed of 25 mm/s. Under this optimum condition solid cylinder along with cone, hollow cylinder and hollow sphere has been fabricated. Fig. 5 shows the photographic view of fabricated parts at optimum condition. At this optimum condition the surface roughness R_a value of 8.43 µm of solid cylinder surface has been obtained.

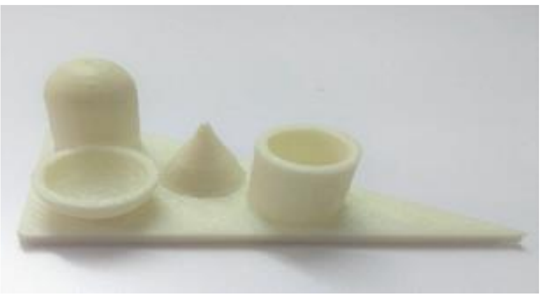

Fig. 5 Photographic view of fabricated parts

5. CONCLUSIONS

The present analysis highlights that diametrical deviation and circularity error of FDM process to fabricate ABS part are affected by process parameters, many of which are within the control of the user. Response surface methodology is used to establish the empirical model of FDM process. The influence of different process parameter such as layer thickness, bed temperature, extruder temp, fill density, speed on FDM responses are exhibited through response surface plot. From basic parametric studies, it is observed that the layer thickness and bed temperature are the most significant parameters which have greater influences on diametrical deviation of fabricated ABS parts. Layer thickness, extruded temperature and print speed are the most significant process parameters for controlling circularity error. From ANOVA it is found mathematical model on diametrical deviation and circularity error are found as adequate to analyze the effect of process parameters on response characteristics of FDM parts with ABS. From the response surface plot based on RSM models it is observed that lower value of diametrical deviation has been observed at low value of bed temperature and moderate value of layer thickness. It also has been found that minimum value of circularity error has been observed at high speed and lower value of layer height. Lower value of circularity error has been observed at lower value of extruder temperature and moderate value of fill density.

Further analysis on surface quality of various geometrical features of FDM fabricated ABS parts have to be carried out for industrial applications.

References:

[1] Sood A. K., Ohdar R. K. And Mahapatra S. S., “Improving dimensional Acuuracy Of Processed Part Using Grey Taguchi Method”, Journal Of Materials And Design, Vol. 30, 4243-4252, (2009).

[2] K. Senthilkumaran, P.M. Pandey, And P.V.M. Rao, “Influence Of Building Strategies On The Accuracy Of Parts In Selective Laser Sintering” Materials & Design, Vol. 30, 2946-2954, (2009).

[3] Anitha R., Arunachalam S., Radhakrishnan P., “Critical Parameters Influencing the Quality Of Prototypes In Fused Deposition Modelling” Journal Of Material Science Technology, Vol. 118, pp. 385-388, (2001).

[4] J. Har And K. Lee, “The Development Of A CAD Environment To Determine The Preferred Build-Up Direction For Layered Manufacturing” International Journal Of Advanced Manufacturing Technology, Vol.14, 247-254, (1998).

[5] Khan Z.A., Lee B. H., Abdullah J., “Optimization Of Rapid Prototyping Parameters For Production Of Flexible ABS Object”, Journal Of Material Processing Technology, 169, 54-61, (2005).

[6] W. Cao and Y. Miyamoto, “Direct slicing from Autocad solid models for Rapid Prototyping” International Journal Of Advanced Manufacturing Technology, 21, 739-742, (2003).