Experimental Evaluation of FDM Process for Model Material Volume Optimization for Cylindrical Primitives

Manu Srivastava, Sachin Maheshwari, T.K. Kundra

Abstract – Optimization of model volume can go a long way in enhancing the quantitative effectiveness of any layered manufacturing (LM) process. This work exhaustively evaluates the effect of contour width, raster width, raster angle, slice height, orientation and air gap on the model volume requirements for basic constructive solid geometry (CSG) primitives. Models have been derived and evaluated analytically and graphically using response surface methodology (RSM) technique to deduce the effect of aforementioned parameters on the model volume estimation for a Fortus 250mc modeler. This work establishes basic design principles for model volume estimation in a given build volume as well as evaluation of different spatial requirements for model volume optimization for Fortus 250 mc modeler in particular and FDM process in general.

Index Terms – Model volume, Contour width, Raster width, Air gap, Raster angle, Orientation, Slice height, Layout optimization.

◆

1 INTRODUCTION

Rapid prototyping (RP), Generative manufacturing (GM) or Layered manufacturing (LM) offers numerous advancements over the conventional manufacturing processes for prototyping purpose. Qualitative and quantitative optimization of layered manufacturing processes has been a subject of great interest to the researchers. Optimization of build time, support volume, model volume and production cost are the key aspects of quantitative optimization whereas qualitative optimization encompasses optimization of surface quality, dimensional accuracy and mechanical properties. Models have been derived and analyzed for basic cylindrical primitives used in Constructive Solid Geometry (C.S.G.).

This paper proposes a novel method of optimization and evaluation of model volume for different feasible orientations at the design stage itself by virtue of model estimation using RSM and its corresponding validation. These estimates combined with build time, support material and production cost estimations can be used for overall quantitative optimization of the FDM process.

2 LITERATURE REVIEW

LM is an advanced manufacturing technique whose success is based on optimal process parameters and technique selection for the desired end results which vary with the end user priorities. The aim of this study is to understand the dependence of model material on different process parameters and to arrive at optimum part orientation for model material usage in FDM process.

Espalin et al. [1] investigated build process variation for FDM in making contours and rasters using variable layer thicknesses and road widths and evaluated its effect on surface roughness, production times and mechanical properties. They used this to develop a unique FDM process which enabled multiple material depositions (F.G.M.). Vilalpando et al.[2] proposed a method to create reconfigurable internal structure to balance mechanical properties, material usage and build time.

A. Sheriff El-Gizawy et al. used polyeterimide (ULTEM 9085) with FDM and characterized the mechanical properties and internal structure evolved using classical lamination theory [3].Panda et al.[4]

Corresponding Author: *Manu Srivastava,*
Division of Manufacturing Processes and Automation Engineering,
Netaji Subhas Institute of Technology, New Delhi
Email: manyash@gmail.com

considered the effect of five important process parameters viz. layer thickness, orientation, raster angle, raster width and air gap on tensile flexural and impact strength using central composite design and empirical model development. After validation using ANOVA theoretical parameter settings to simultaneously affect all three response optimization are suggested. Jacobs [5] gave some basic guidelines for best orientation for part build which are still followed. Choi et al. [6] proposed a virtual reality system for modeling and optimization of RP processes and by building a mathematical model for build-time estimation in SLS systems. Zhe [7] presented relationships between the build orientation and the maximum stress, maximum strain, and young's modulus for SLS, FDM and Objet (SLA), decision criteria for selecting the best orientation of the minimum strain and maximum external load through case studies. Mishra et al. have also reviewed the build orientations for different RP processes [8].

Model material estimation is one of the critical responses in the quantitative optimization of the LM processes. A number of researchers have carried work in improving the effectiveness and efficiency of FDM processes. A lot of work has been done in the direction of qualitative improvements. However, from detailed literature review we have come to the conclusion that there are research gaps in the quantitative aspect of the of the FDM process optimization. Models have been derived and analyzed for the model material estimation of the fused deposition modeling process in the current study.

3 MODEL MATERIAL

The model material is the amount of raw material used for making the component. Fortus 250mc modeler uses ABSP430 as the model material. This material is pretty expensive and significant savings in cost can be obtained if optimally use it. Its requirement varies from one application to the other. For instance, if porous scaffolds are required then the process would be designed for minimum model material. On the other hand for robust and dense service models, the model material used should be more. For general prototyping applications where the utility of models is only an extension of the three dimensional physical geometric verification, we can safely assume that the aim would be to minimize the model material volume.

4 EXPERIMENTAL DESIGN

4.1 Modeler: We have carried out our experiments on Insightv9.1 for Fortus 250 mc modeler.

4.2 Fixed parameters: Based on previous experimentations and trial experimental designs, we rounded upon following parameters as the fixed parameters [Table 1].

4.3 Process parameters: Based upon trial experimentations and the work of previous researchers, we concluded that the following machine parameters can be taken as the process parameters for optimization of build time.[Table 2]

TABLE 1: FIXED PARAMETERS

S.No.	Parameter	Comments
i.	Part interior style	Solid normal
ii.	Visible surface style	Normal
iii.	Support style	Sparse
iv.	Model Material	ABS P430
v.	Support Material	ABS SR30
vi.	Part fill style	one contour/rasters
vii.	Part X Shrink Factor	1.007
viii.	Part Y shrink factor	1.007
ix.	Contour to raster air gap	0
x.	support style	Sparse
xi.	Support self supporting angle	50
xii.	Contour base oversize	1.27
xiii.	Contour base layers	8
xiv.	Invert material	yes

xv.	Support tip	T16

TABLE 2 : PROCESS PARAMETERS

S.No.	Parameters	Level 1	Level 2	Level 3
1	Slice height(mm)	0.1778	0.254	0.3302
2	Contour width(mm)	0.4	0.48	0.56
3	Air gap(mm)	-0.1	0.4	0.9
4	Raster width(mm)	0.4	0.48	0.56
5	Raster angle(degrees)	0	15	30
6	Orientation(degrees)	0	15	30

TABLE 3: SCHEME OF EXPERIMENTATION

Primitive		Spatial Rotation about				
S.No.	Type	x axis(θx)	Y-axis(θy)	z axis(θz)	y with min z (θxz)	y with min z (θyz)
1	Cylinder	C1PS3	C1PS4	C1PS5	C1PS1	C1PS2

Note: CnPSm implies the evaluations for nth component at mth spatial orientation (1-5)

4.4 Design Methodology: The design methodology adopted was response surface methodology. The RSM table that was used was a 86 run table full factorial design table for 6 process parameters and is given in table 4.The scheme of experimentation followed to evaluate the effect of spatial orientation is given in table 3.

5 RESPONSE

A single response model material volume is evaluated in all possible orientations in the given build volume of the modeler with respect to six different process parameters. The experiment has been designed using response surface methodology and models corresponding to each parameter setting (CnPSm) have been derived. The graphs of these settings are made and compared for all the other parameter settings for the same component and the optimal conditions are concluded.

6 RESULTS

The model obtained using RSM for C1PS1 (cylinder with absolute rotation about x-axis keeping minimum z-height) is discussed.

TABLE 4: CYLINDER WITH ABSOLUTE ROTATION ABOUT X-AXIS KEEPING MINIMUM Z HEIGHT, C1PS1:

Std	Run	Factor 1 A: Slice Height	Factor 2 B: Counter..mm	Factor 3 C Air Gap in mm	Factor 4 D: Raster in mm	Factor 5 E: Raster a...degrees	Factor 6 F: Orientation degrees	Response 1 Model material volume,cm3
13	1	0.1778	0.4	0.9	0.56	0	0	9.754
27	2	0.1778	0.56	-0.1	0.56	30	0	26.778
72	3	0.254	0.48	0.4	0.56	15	15	13.685
30	4	0.3302	0.4	0.9	0.56	30	0	10.088
60	5	0.3302	0.56	-0.1	0.56	30	30	26.549
53	6	0.1778	0.4	0.9	0.4	30	30	8.566
28	7	0.3302	0.56	-0.1	0.56	30	0	26.681
9	8	0.1778	0.4	-0.1	0.56	0	0	26.581
11	9	0.1778	0.56	-0.1	0.56	0	0	26.426
61	10	0.1778	0.4	0.9	0.56	30	30	10.247
39	11	0.1778	0.56	0.9	0.4	0	30	8.944
45	12	0.1778	0.4	0.9	0.56	0	30	10.16

38	13	0.3302	0.4	0.9	0.4	0	30	8.466
84	14	0.254	0.48	0.4	0.48	15	15	13.413
52	15	0.3302	0.56	-0.1	0.4	30	30	28.872
82	16	0.254	0.48	0.4	0.48	15	15	13.413
19	17	0.1778	0.56	-0.1	0.4	30	0	29.099
69	18	0.254	0.48	-0.1	0.48	15	15	27.852
43	19	0.1778	0.56	-0.1	0.56	0	30	26.536
73	20	0.254	0.48	0.4	0.48	0	15	13.265
46	21	0.3302	0.4	0.9	0.56	0	30	10.104
5	22	0.1778	0.4	0.9	0.48	0	0	8.236
34	23	0.3302	0.4	-0.1	0.4	0	30	29.01
20	24	0.3302	0.56	-0.1	0.4	30	0	28.997
48	25	0.3302	0.56	0.9	0.56	0	30	10.486
41	26	0.1778	0.4	-0.1	0.56	0	30	26.678
26	27	0.3302	0.4	-0.1	0.56	30	0	26.804
21	28	0.1778	0.4	0.9	0.4	30	0	8.451
1	29	0.1778	0.4	-0.1	0.4	0	0	29.01
32	30	0.3302	0.56	0.9	0.56	30	0	10.406
79	31	0.2540	0.48	0.4	0.48	15	15	13.413
37	32	0.1778	0.4	0.9	0.4	0	30	8.52
35	33	0.1778	0.56	-0.1	0.4	0	30	28.876
8	34	0.3302	0.56	0.9	0.4	0	0	8.547
36	35	0.3302	0.56	-0.1	0.4	0	30	28.804
76	36	0.2540	0.48	0.4	0.48	15	30	13.487
10	37	0.3302	0.4	-0.1	0.56	0	0	26.498
23	38	0.1778	0.56	0.9	0.4	30	0	8.821
33	39	0.1778	0.4	-0.1	0.4	0	30	29.071
14	40	0.3302	0.4	0.9	0.56	0	0	9.752
81	41	0.2540	0.48	0.4	0.48	15	15	13.413
7	42	0.1778	0.56	0.9	0.4	0	0	8.623
75	43	0.2540	0.48	0.4	0.48	15	0	13.393
71	44	0.2540	0.48	0.4	0.4	15	15	13.577
58	45	0.3302	0.4	-0.1	0.56	30	30	26.696
74	46	0.2540	0.48	0.4	0.48	30	15	13.441
44	47	0.3302	0.56	-0.1	0.56	0	30	26.465
47	48	0.1778	0.56	0.9	0.56	0	30	10.548
65	49	0.1778	0.48	0.4	0.48	15	15	13.464
17	50	0.1778	0.4	-0.1	0.4	30	0	29.277
2	51	0.3302	0.4	-0.1	0.4	0	0	28.941
42	52	0.3302	0.4	-0.1	0.56	0	30	26.619
51	53	0.1778	0.56	-0.1	0.4	30	30	28.949
3	54	0.1778	0.56	-0.1	0.4	0	0	28.845
56	55	0.3302	0.56	0.9	0.4	30	30	8.931
55	56	0.1778	0.56	0.9	0.4	30	30	8.985
59	57	0.1778	0.56	-0.1	0.56	30	30	26.622
12	58	0.3302	0.56	-0.1	0.56	0	0	26.368
66	59	0.3302	0.48	0.4	0.48	15	15	13.401
18	60	0.3302	0.4	-0.1	0.4	30	0	29.185
40	61	0.3302	0.56	0.9	0.4	0	30	8.883
68	62	0.2540	0.56	0.4	0.48	15	15	13.541
62	63	0.3302	0.4	0.9	0.56	30	30	10.198
24	64	0.3302	0.56	0.9	0.4	30	0	8.746

80	65	0.2540	0.48	0.4	0.48	15	15	13.413
54	66	0.3302	0.4	0.9	0.4	30	30	8.521
57	67	0.1778	0.4	-0.1	0.56	30	30	26.762
31	68	0.1778	0.56	0.9	0.56	30	0	10.486
6	69	0.3302	0.4	0.9	0.4	0	0	8.167
49	70	0.1778	0.4	-0.1	0.4	30	30	29.148
16	71	0.3302	0.56	0.9	0.56	0	0	10.117
86	72	0.2540	0.48	0.4	0.48	15	15	13.413
22	73	0.3302	0.4	0.9	0.4	30	0	8.387
64	74	0.3302	0.56	0.9	0.56	30	30	10.52
4	75	0.3302	0.56	-0.1	0.4	0	0	28.767
70	76	0.2540	0.48	0.9	0.48	15	15	9.395
83	77	0.2540	0.48	0.4	0.48	15	15	13.413
78	78	0.2540	0.48	0.4	0.48	15	15	13.413
77	79	0.2540	0.48	0.4	0.48	15	15	13.413
25	80	0.1778	0.4	-0.1	0.56	30	0	26.893
15	81	0.1778	0.56	0.9	0.56	0	0	10.193
63	82	0.1778	0.56	0.9	0.56	30	30	10.579
50	83	0.3302	0.4	-0.1	0.4	30	30	29.08
67	84	0.254	0.4	0.1	0.48	15	15	13.396
29	85	0.1778	0.4	0.9	0.56	30	0	10.155
85	86	0.254	0.48	0.4	0.48	15	15	13.413

TABLE 5: RSM MODEL SPECIFICATIONS FOR C1PS1

Transform	Lambda	Process order	Pure error	R-Squared	Adjusted R-Squared
Power	0.63	Backward elimination	0	0.9857	0.979

RSM model details are tabulated in Table 5.The model was found to be significant with F value of 1959.30 and p-value < 0.0001. Fig. 1 shows the normal probability plot of residuals for model material volume. It is evident that all the residuals are clustered in the straight line implying that errors are normally distributed. Fig. 2 shows the plot of actual vs predicted model values. Since the points are clustered around a straight line,the predicted value are in close adherence to the actual values. Normal plot of residuals and Predicted versus Actual graphs are attached below.

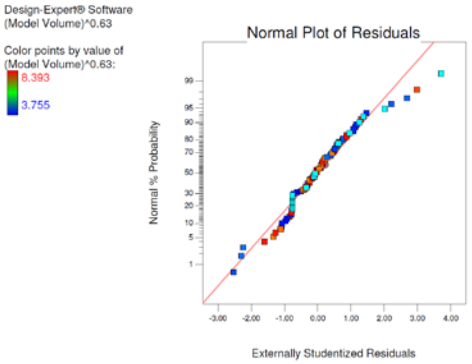

Fig. 1: Normal plot of residuals

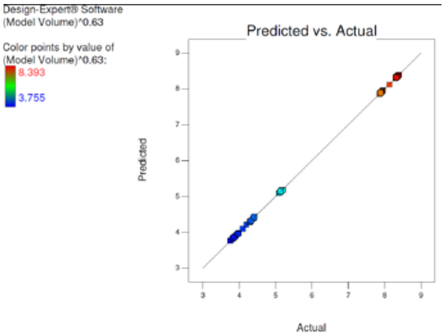

Fig. 2: Predicted versus Actual

The Final model Equation for model material volume in terms of Actual Factors:

(Model Volume) 0.63 = +9.77970-0.099461 * Slice Height-0.10448 * Contour Width-10.21377 * Air Gap -7.78119 * Raster Width+4.70344E-003 * Raster angle+8.76200E-004 * Orientation+0.83872 * Contour Width * Air Gap+5.52299 * Air Gap * Raster Width+3.65889E-004 * Air Gap * Raster angle+2.29641E-003 * Air Gap * Orientation+2.56203E-003 * Raster Width * Raster angle-5.40118E-005 *

Raster angle * Orientation+3.87733 * Air Gap2+5.80004 * Raster Width2-1.32314E-004 * Raster angle2

Figures 3-8 denote the variation of build-time with respect to the changes in slice height, contour width, air gap, raster width raster angle and orientation respectively for the rotation of cylinder with about x-axis keeping z height minimum.

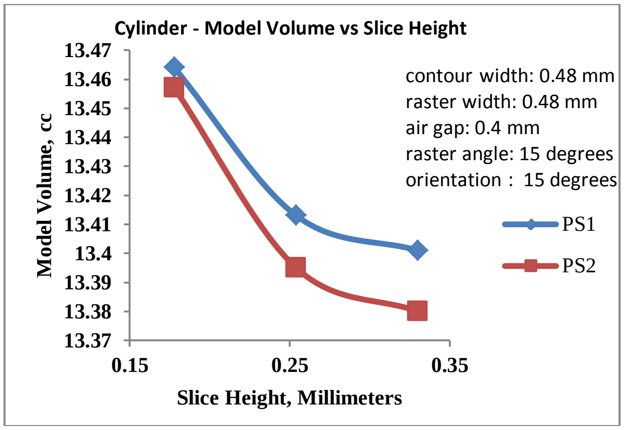

Fig. 3: Variation of model volume with slice height

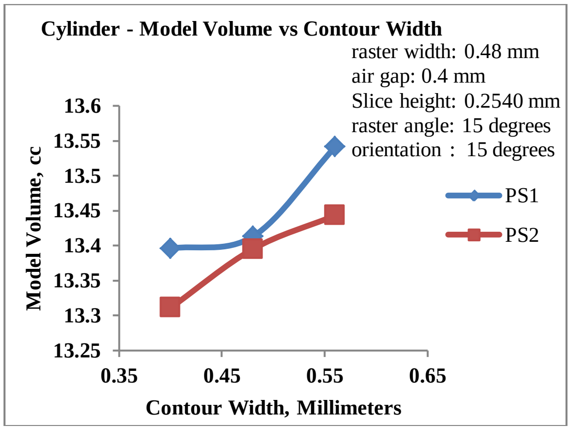

Fig. 4: Variation of model volume with contour width

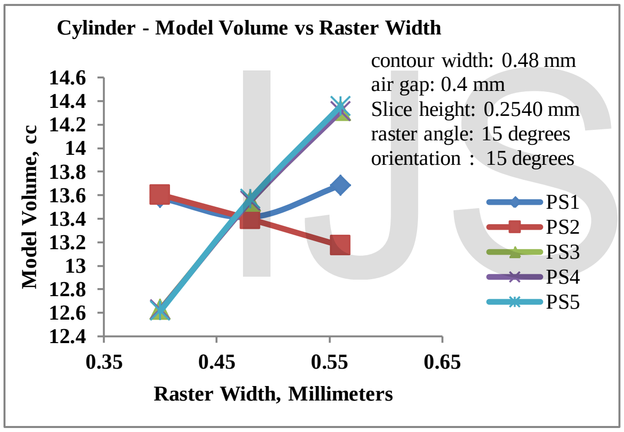

Fig. 5: Variation of model volume with raster width

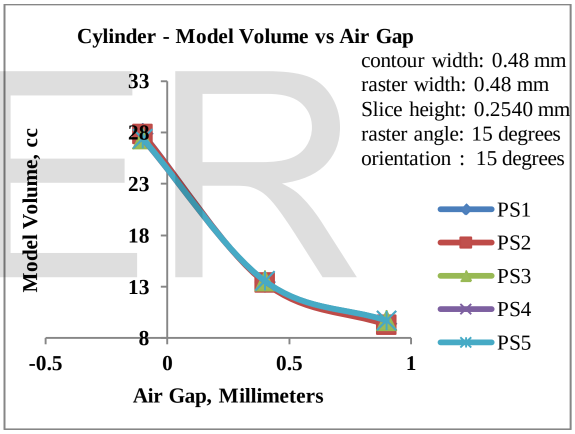

Fig. 6: Variation of model volume with air gap

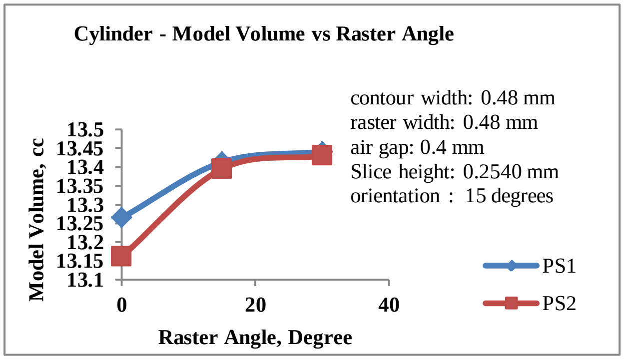

Fig. 7: Variation of model volume with raster angle

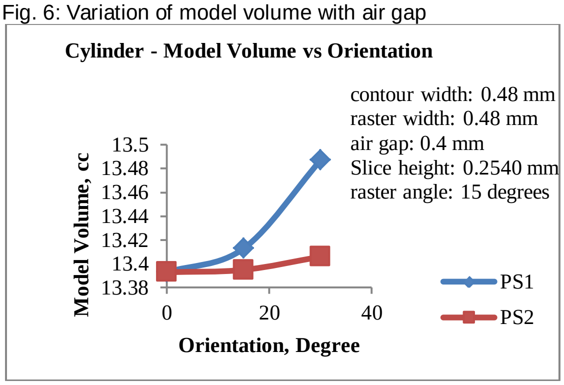

Fig. 8: Variation of model volume with orientation

Convulsive to the model formation for C1PS1, models have been made for every component corresponding to all parameter settings by experimental observation and modeling. The same have been analyzed and the following conclusions have been drawn:

1. Effect of each individual parameter on the build time.
2. Best spatial Orientation for Cylindrical component.

7 CONCLUSIONS

This study experimentally builds the model for the model material volume with respect to:

i) All six crucial process parameters and from the results the following can be safely concluded [Table 7]:

M.V. shows a fluctuating behavior with increase in slice height. It increases, remains constant and decreases in different conditions.

M.V. invariably increases with increase in air gap.

M.V. invariably increases corresponding to increasing contour width.

M.V. invariably increases corresponding to increasing raster width.

M.V increases with increase in raster angle in general though the increase is minor. Also, there is a fluctuation around the middle value in many cases implying no clear trend.

M.V increases with increase in angle of rotation from any axis (orientation) in general though the increase is minor. Also, there is a fluctuation around the middle value in many cases implying no clear trend.

ii) Every feasible spatial orientation and from the results the following can be safely concluded [Table 8]:

For cylindrical primitives, rotation about θyz gives the least value of build-time followed by rotations θz, θx & θy, θxz.

TABLE 7: DEPENDENCE OF MODEL MATERIAL VOLUME (M.V.) ON INDIVIDUAL PROCESS PARAMETERS FOR PRIMITIVES

Componer Name	Slice Height (S.H.)	Contour Width (C.W.)	Air Gap (A.G.)	Raster width (R.W.)	Raster angle (R.A.)	Orientation (0)
Cylindrical Primitive	M.V. decreases wit increase in S.H. for P.S.1&2; remains unaffected for P.S.2,3&4.	M.V. decreases with increase in C.W. for P.S.1& remains unaffected for P.S.2,3&4.	M.V. invariably decreases with increase in A.G.	M.V. decrease with increase in R.W. for PS1&2; increases for increase in R.W. for PS3,4&5	M.V. increases with increase in R.A. for P.S. 1&2; remains unaffected for P.S.2,3&4.	M.V. increases with increase in C for P.S. 1&2; remains unaffected for P.S.2,3&4.

TABLE 8 VARIATION OF BUILD TIME WITH SPATIAL ORIENTATION FOR PRIMITIVES

Process Parameters	Effect on M.V.	Rotation about x axis(θx)	Rotation about y axis (θy)	Rotation about z axis(θz)	Rotation about x axis with minimum z (θxz)	Rotation about y axis with minimum z (θyz)
B.T. Variation: Scale 0-5 where 0 implies no variation and 5 implies maximum variation. Values: Scale 1-5 where 1 implies least value and 5 implies maximum value.						
Cylindrical Primitive						
Slice height	Values	3	4	5	2	1
	Variation	0	0	0	2	1
Contour width	Values	3	4	5	2	1
	Variation	0	0	0	2	1
Air gap	Values	3	4	5	2	1
	Variation	3	3	4	2	1
Raster width	Values	3	4	5	2	1
	Variation	0	0	0	2	1
Raster angle	Values	3	4	5	2	1
	Variation	0	0	0	2	1
Orientation	Values	3	4	5	2	1
	Variation	0	0	0	2	1

Raster width	Values	3	2	1	4	5
	Variation	3	2	1	4	5
Raster angle	Values	3	2	1	4	5
	Variation	3	2	1	4	0
Orientation	Values	3	2	1	4	5
	Variation	3	2	1	4	5

8 REFERENCES

1. Zhang X., Zhou B., Zeng Y., Gu P. Model layout optimization for solid ground curing rapid prototyping processes; Robotics and Computer Integrated Manufacturing 18 (2002) 41–51
2. Espalin D., Ramirez J.A., Medina F., Wicker R.; " Multimaterial, multitechnology FDM: Exploring build process variations";Rapid prototyping journal-Emerald Insight; Volume 20,issue 3;Pg. 236-244;2014
3. Vilalpando L., Urbanic J.; "Parametric internal matrix structure for components made by Fused Deposition Modelling";4th International conference on changeable, agile, reconfigurable and virtual production(CARV2011); pg. 287-291,2011
4. El-Gizawy S., Corl S., Graybill B. ; www.stratasys.com/fdmproducts.pdf; web.[14 September 2014]
5. Panda S.K., Padhee S, Sood A.K., Mohapatra S.S.; "Optimization of fused deposition modeling process parameters using bacterial foraging technique";Intelligent information management; volume 1; pp. 89-97; 2009.
6. Jacobs, P.F., Rapid Prototyping and Manufacturing: Fundamentals of Stereolithography, Society of Manufacturing Engineers, 1994.
7. Choi S.H., Samavedam S., Modelling and optimization of rapid prototyping, Computers in industry, Elsevier, 47, pp 39-43, 2002.
8. Zhe C., Selection of Optimal Build Orientation with Minimum Strain and Maximum Strength in Rapid Prototyping, The University of Hong Kong, MS thesis, 2010.
9. Mishra A.K. and Thirumavalavan S., A Study of Part Orientation in Rapid Prototyping, Middle-East Journal of Scientific Research 20 (9): 1197-1201, 2014.
10. Yim S.S. and Rosen D.; "Build-time and cost models for additive manufacturing process selection; 32nd International Design engineering technical conferences and computers and information in engineering conference; Vol 2; ASME Proceedings; 2012.
11. Stratasys Data Sheets: The truth about speeds; www.stratasys.com; web.[September 14,2014]
12. Zhu Z. et al; Pg 160; "Advances in sustainable and competitive manufacturing systems"; 23rd International conference on flexible automation and intelligent manufacturing; Vol 1; Springer; 2013.
13. www.stratasys.com/selections-applications; "Finishing touch smoothing station: Expanding possibilities"; web[14 September 2014].
14. Fused deposition modeling (FDM): custompart.net; web; 2010.
15. Kruth, J.P., ''Material Incress Manufacturing by Rapid Prototyping Techniques," Annals of the CIRP, Keynote Paper, Vol.41/2, pp. 603–614, 1990.
16. Bablani M. and Bagchi A., Quantification of errors in rapid prototyping processes, and determination of preferred orientation of parts, Product Realization Laboratory, Center for Advanced Manufacturing, Clemson University, Report.

Authors:
[1]Manu Srivastava, [1]Sachin Maheshwari, [2]T.K. Kundra

[1]Division of Manufacturing Processes and Automation Engineering,
Netaji Subhas Institute of Technology, New Delhi

(manyash@gmail.com, ssaacchhiinn@gmail.com)
[2] Department of Mechanical Engineering,
Indian Institute of Technology, New Delhi
(tkkundra@gmail.com)