International Journal on Emerging Technologies **1**(2): 106-111(2010) **ISSN : 0975-8364**

An experimental investigation on surface quality and dimensional accuracy of FDM components

T. Nancharaiah *D. Ranga Raju and **V. Ramachandra Raju

Department of Mechanical Engineering, D.M.S.S.V.H College of Engineering, Machilipatnam –521002, A.P., India

**S.R.K.R. Engineering college, Bhimavaram, W.G. (A.P.) India .*

***JNTU College of Engineering, Vizayanagaram, (A.P.) India.*

ABSTRACT : This paper describes an experimental design technique for determining the optimum surface finish and dimensional accuracy of a part built by the Fused Deposition Modeling (FDM) process. The design investigates the effect of the process parameters layer thickness, road width, raster angle and air gap on the surface finish and dimensional accuracy. Experiments were conducted using Taguchi's design of experiments with three levels for each factor. The results are statistically analyzed to determine the significant factors and their interactions. From the ANOVA analysis, it was found that the layer thickness and road width affect the surface quality and part accuracy greatly. Raster angle has little effect. But air gap has more effect on dimensional accuracy and little effect on surface quality.

Keywords : Rapid Prototyping, Fused Deposition Modeling, Taguchi¢s design of experiments.

I. INTRODUCTION

Rapid prototyping (RP) is an advanced manufacturing technology commercialized in the middle of 1980s. At present, RP technology is widely used in engineering for conceptual models and functional models. The application of RP has been shown to greatly shorten the design-manufacturing cycle, hence reducing the cost of product and increasing competitiveness. Further development of this technology is focusing on short and long term tooling which again has been shown in some cases, and promises in many cases, to reduce costs and cycle times. There are many commercial RP systems available in the market today such as Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), Solid Ground Curing (SGC) and Three Dimensional Printing (3DP) etc. All RP systems have a limit on the type and properties of material that can be fabricated. The Fused Deposition Modeling (FDM) process from Stratasys produces prototype parts out of ABS plastics.

Over the last 10 years, the RP industry has undergone significant improvements in developing machines and materials that fabricate the production-representative prototypes. These prototypes are also to form, fit and functional testing as well as ergonomic evolution. Several attempts have been made to make a systematic analysis of errors and the quality of the prototypes. The effect of two important built parameters in SL (hatching space and curing depth) as well as of post-processing treatment (UV and thermal curing) to the magnitude of the resulting residual stresses [1]. The properties of ABS parts fabricated by the FDM 1650. Using a design of experiments (DOE) approach, the process parameters of FDM were examined. [2] Pulak M. Pandey et al. carried out fractional factorial experiments to improvements of surface finish by staircase machining in fused deposition modeling, with two levels and four process parameters is adopted to understand the effect of various process variables. Anitha et al. [4] has studied the various process parameters used in FDM affect the quality characteristics of the prototypes using Taguchi technique. Therefore in this present research, the FDM process parameters viz; layer thickness, road width, air gap and raster angle for their influence on physical properties like surface finish, dimensional accuracy are considered. Further these process parameters are optimized and the effect of each parameter on the part quality is also investigated using appropriate statistical techniques. Thus the contribution to this extent will definitely help in improving the quality of prototypes in FDM process as well as simplifying the selection of optimal process parameters for desired quality standards.

II. FABRICATION PARAMETERS IN FDM PROCESS

When preparing to build FDM parts, many fabrication parameters are needed in the software. To achieve optimum quality, these parameters are set differently according to requirements of applications. Therefore, the first step in the experiment was to identify the process control parameters that are likely to affect the quality of FDM parts. The selected parameters are listed below.

Layer thickness: Slice height is the thickness of each layer measured in the vertical or Z direction as shown in figure (1). Varying the slice height would most likely have the same effect as varying the bead width of the ABS plastic. *Bead width*: Bead width is the thickness of the bead (or road) that the FDM nozzle deposits as shown in Fig. 1.

Raster angle: It is the angle between the two consecutive layers. Fig. 2 shows the position of raster angle.

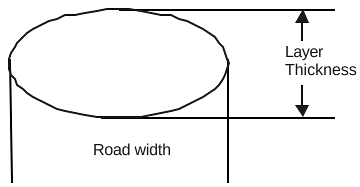

Fig. 1.

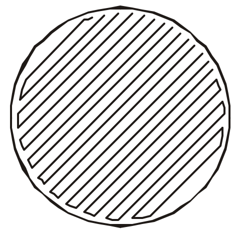

Fig. 2. Raster orientations

A. Assumptions

The following process parameters namely envelope temperature (the temperature of the air around the part), model temperature, and nozzle diameter (the width of the hole through which the material extrudes) are neglected. The nozzle diameter was assumed to primarily affect the geometry of the bead. Since bead geometry was already being altered via road width (which is controlled by the flow rate of material through the nozzle), altering the nozzle diameter seemed to duplicate the testing. Effecting a nozzle change, which requires a physical transfer and re-calibration for every change, is much more time consuming than changing road width, which can be easily modified in software.

Air gap: Air gap is the space between the beads of FDM material as shown in Fig. 3. The default is zero, meaning that the beads just touch. It can be modified to leave a positive gap, which means that the beads of material do not touch. The positive gap results in a loosely packed structure that builds rapidly. The air gap value can also be modified to leave a negative gap, meaning that two beads partially occupy the same space. This results in a dense structure, which requires a longer build time.

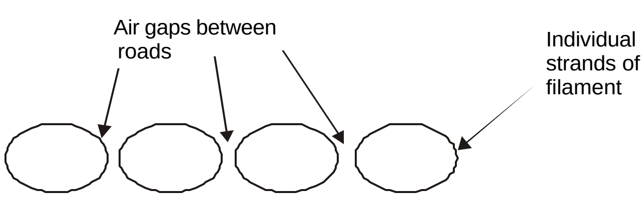

Fig. 3. Cross section of a layer showing roads and the air gap between roads.

III. TAGUCHI METHOD

The Taguchi design of experiment method was used in this project to evaluate the relative contribution of process parameters on surface quality and dimensional accuracy of FDM parts. According to Taguchi method, quality characteristic is a parameter whose variation has a critical effect on product quality, e.g., weight, cost, dimensional accuracy, surface finish, etc. Taguchi method uses a special set of arrays called orthogonal arrays. These standard arrays stipulate the way of conducting the minimum number of experiments, which would give the full information of all factors that affect the performance parameters. The selected process parameters affecting the quality of FDM parts and their levels are given in Table 1. Due to limitation on parameters the L18 array [11] was chosen. Table 2 shows the L18 array.

Table 1: List of Process Parameters considered and their levels

Factors	Symbol	Level 1	Level 2	Level 3
Layer thickness (mm)	A	0.1778	0.254	0.33
Road width (mm)	B	0.3048	0.5132	0.7258
Raster angle in (deg.)	C	0	30	45
Air gap (mm)	D	–0.0010	0.000	+ 0.0010

Table 2 : L18 Orthogonal array used in the experiment

Trail No.	Dummy level	Layer tinck-ness	Road width	Dummy Level	Raster angle	Layer thick ness X Raster angle	Road width X Raster angle	Air gap
1	0	1	1	0	1	1	1	1
2	0	1	2	0	2	2	2	2
3	0	1	3	0	3	3	3	3
4	0	2	1	0	2	2	3	3
5	0	2	2	0	3	3	1	1
6	0	2	3	0	1	1	2	2
7	0	3	1	0	1	3	2	3
8	0	3	2	0	2	1	3	1
9	0	3	3	0	3	2	1	2
10	0	1	1	0	3	2	2	1
11	0	1	2	0	1	3	3	2
12	0	1	3	0	2	1	1	3
13	0	2	1	0	3	1	3	2
14	0	2	2	0	1	2	1	3
15	0	2	3	0	2	3	2	1
16	0	3	1	0	2	3	1	2
17	0	3	2	0	3	1	2	3
18	0	3	3	0	1	2	3	1

IV. EXPERIMENTAL PROCEDURE

A trial run was performed in which a series of samples were built on the FDM Prodigy Plus machine. The dimensions of the samples were chosen according to ASTM D 695 specimen, 25.4 mm in length (height) and 12.7 mm in diameter, shown in Fig. 4. Totally 18 samples were produced by FDM according to the L18 array.

A. Prodigy plus FDM machine

Prodigy Plus builds parts, including internal features, directly from CAD .stl files. The system builds three-dimensional parts by extruding a bead of ABS plastic through a computer-controlled extrusion head, producing high quality parts that are ready to use immediately after completion. With three layer resolution settings, it can be choose to build a part quickly for design verification, or finer settings for higher quality surface detail also can be choose. The Prodigy Plus system consists of two main components - the machine itself and insight, the preprocessing software that runs on a Windows NT, Windows 2000, or Windows XP platform.

Prodigy Plus's build envelope measures 203 × 203 × 305 mm (8 × 8 × 12 in). Each material cartridge contains 922 cc (56.3 cu.in.) of usable material - enough to build continuously for about four days without reloading. Fig. 4 (a) shows the Prodigy Plus machine

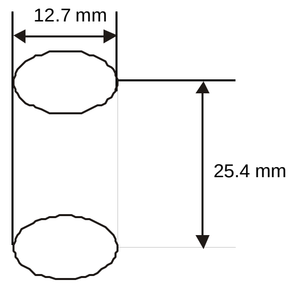

Fig. 4. Test specimen **Fig. 4(a)** Prodigy plus FDM Machine.

B. Part accuracy

Minimum deviation between fabricated part dimension and CAD model dimension was selected as one of the part accuracy criteria. To measure the deviation, each axis (x,y and z) was studied separately. For finding deviation, the height (z) values of the fabricated parts were measured using micrometer. The deviations from CAD model dimension along height were shown in Fig. 6.

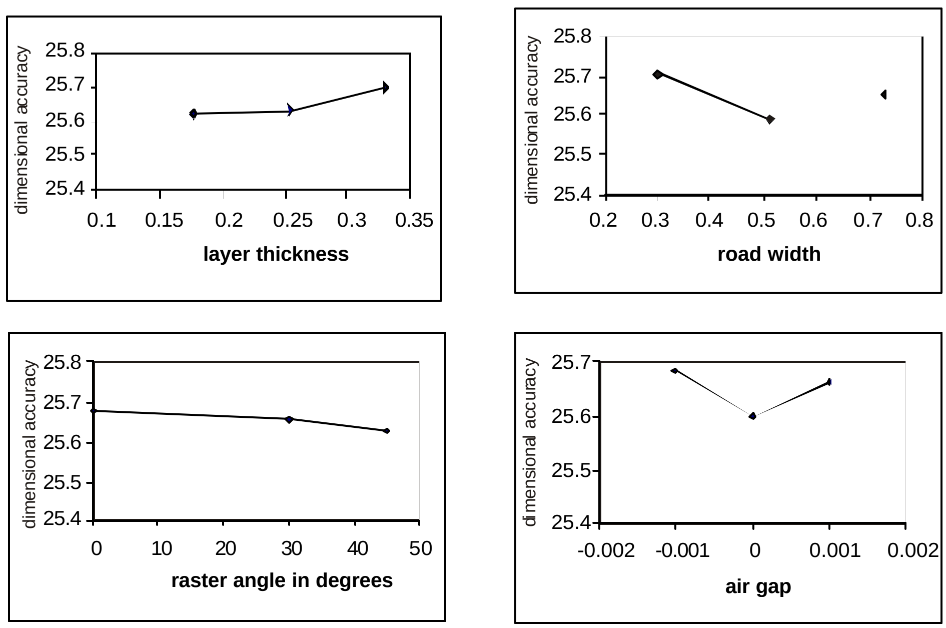

Fig. 6. Variation of dimensional accuracy with build parameters (*i.e.* layer thickness, road width raster angle and air gap)

C. Surface quality

Samples are built according to L18 array at differentsettings of the parameters. The roughness values on the surface of the samples were obtained by using a surf test, a contact type of surface measurement system. Each measurement was taken over a length of 8 mm. Ra, the roughness value is calculated as per center line average (CLA) method.

V. RESULTS AND DISCUSSION

The study involved 18 sample components produced by FDM Prodigy Plus machine. The variations of the part accuracy with respect to CAD model dimensions were shown in Fig. 6. From the Fig. 7 & 8 it was found that the interaction between layer thickness and raster angle have less effect and the interaction between road width and raster angle have effect significantly. Experimental results for surface roughness values were shown in Fig. 11. From the Fig. 9 & 10 it was found that there is interaction between layer thickness and raster angle, road width and raster angle on surface finish have effect significantly. And also it gives that effect of raster angles was very little and the parameters namely layer thickness, road width, air gaps have significant effect on both roughness and accuracy of the parts.

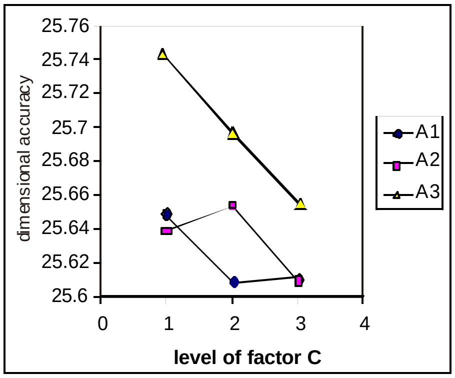

Fig. 7. Interaction plot of Dimensional accuracy vs layer thickness and raster.

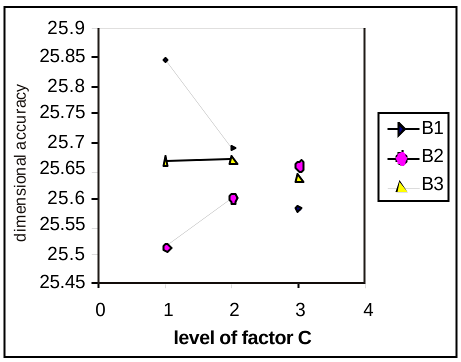

Fig. 8. Interaction plot of Dimensional accuracy vs layer thickness and raster angle.

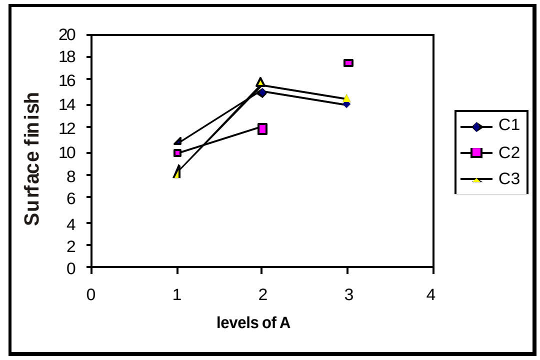

Fig. 9. Interaction plot of surface roughness vs layer thickness and raster angle.

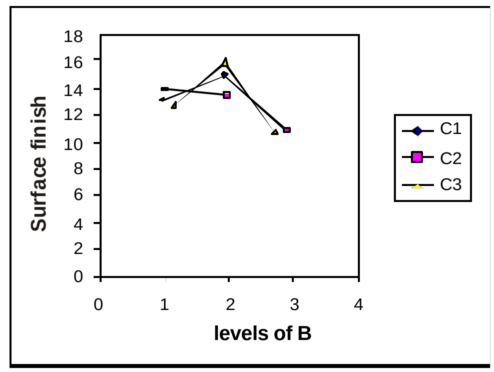

Fig. 10. Interaction plot of surface roughness vs road width and raster angle.

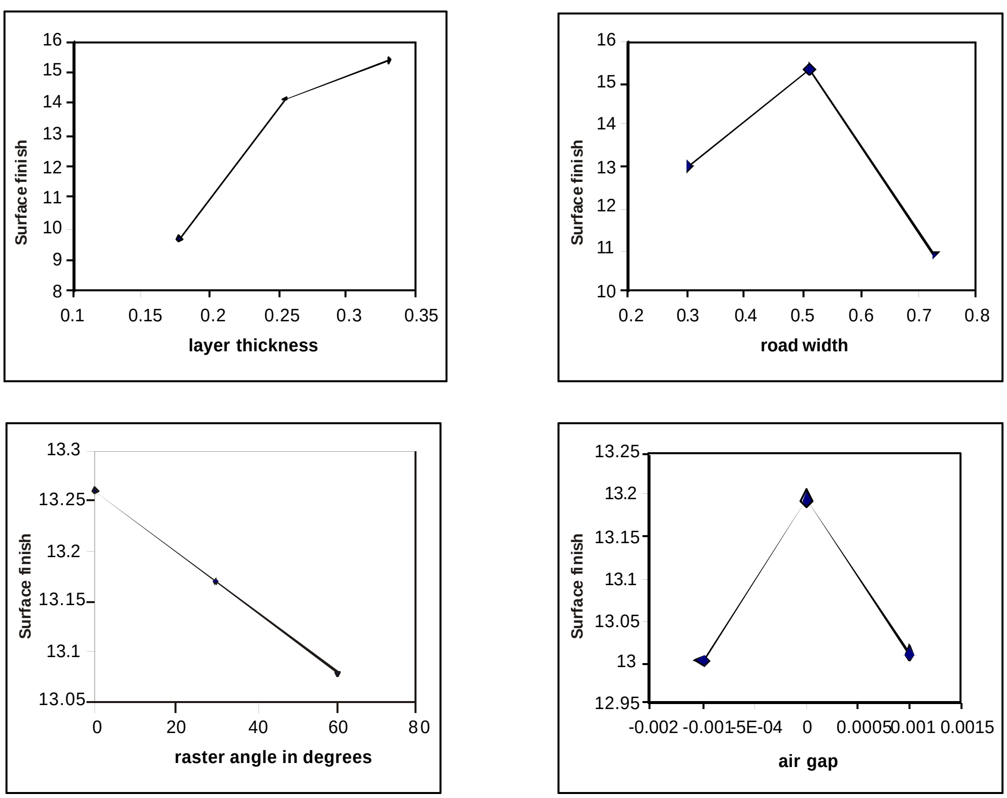

Fig. 11. Variation of Surface finish with build parameters (*i.e.* layer thickness, road width, raster angle and air gap).

A. Signal to noise (S/N) ratio

The signal to noise ratio measures the sensitivity of the quality characteristic being investigated to those uncontrollable external factors. To minimize the problem, the governing relationships for the S/N ratio in terms of the experimentally measured values of Ra, i.e., yi calculated as follows:

$$S/N \text{ ratio} = -10 \log 10 \text{ MSD}$$

Where MSD = $\Sigma (y_i - \hat{y})^2/n$, $\hat{y}$ the target value that is to be achieved, the number of samples. The S/N ratio values obtained for the trials are listed in table (3) & (4).

Table 3 : Signal to noise (S/N) ratio for surface finish:

Factor	Level 1	Level 2	Level 3	L2-L1
Layer thickness	–19.53	–22.818	–23.62	–3.288
Road width	–21.98	–23.54	–20.458	–1.56
Raster angle	–22.15	–22.13	–21.68	+0.02
Air gap	–21.97	–21.93	–21.74	+0.04

Table 4 : Signal to noise (S/N) ratio for dimensional accuracy

Factor	Level 1	Level 2	Level 3	L2-L1
Layer thickness	15.27	12.81	10.69	–2.46
Road width	10.97	15.98	11.82	5.01
Raster angle	13.475	12.19	13.11	–1.285
Air gap	11.16	15.92	11.69	4.76

B. ANOVA analysis

ANOVA analysis provides significance rating of the various factors analyzed in this study. Based on the above rating, factors, which influence the objective function significantly, could be identified and proper control measures adopted. In a similar way, those factors with minimum influence could be suitably modified to suit economic considerations. The ANOVA computations are carried out based on procedure out lined in ref (12) and listed table in (5-7). A variable possessing the maximum value of variance is said to have the most significant effect on the process under consideration.

Table 5 : ANOVA analysis for dimensional accuracy

Factor Freedom	Degree of	Sum of Squares V	Variance,	Contribution %
Layer thickness	2	0.01992	0.00996	12.23
Road width	2	0.038868	0.0194	23.86
Raster angle	2	0.007984	0.003992	4.9
Air gap	2	0.0250867	0.012543	15.4
Layer thickness x raster angle	4	0.01162	0.002905	7.13
Road width x raster angle	4	0.036549	0.009137	22.44
Error	1	0.022844	-----	14.025
Total	17	0.162872	-----	

Table 6: ANOVA analysis for surface finish (with out pooling)

Factor	Degree of Freedom	Sum of Squares	Variance, V	Contribution %
Layer thickness	2	107.9735	53.98675	48.53
Road width	2	60.9927	30.496315	27.36
Raster angle	2	0.7745	0.38725	0.347
Air gap	2	0.1424	0.0712	0.06
Layer thickness x raster angle	4	10.7156	2.6789	4.86
Road width x raster angle	4	24.08075	6.0201815	10.80
Error	1	18.24085	18.24085	
Total	17	222.920	-----	

Table 7: Lis

Factor	Degree of Freedom	Sum of Squares	Variance, V	F-Test	Contribution %
Layer thickness	2	107.9735	53.98675	16.2647	45.45
Road width	2	60.9927	30.496315	9.1868	24.383
Road width x raster angle	4	24.08075	6.0201815	1.8137	4.8
Error	9	29.87335	3.31926	-----	25.367
total	17	222.9203	-----	-----	-----

When the contribution of any factor is small, then the sum of squares, (SS) for that factor is combined with the error (SSe). This process of disregarding the contribution of a selected factor and subsequently adjusting the contributions of the other factors is known as pooling. In this work the effect of raster angle and the interaction between road width and raster angle were found to be negligible effect. Hence they were pooled and the contributions of other factors were significantly changed.

C. Correlation analysis

In process control, the aim is to control the characteristics of the output of the process by controlling a process parameter. One succeeds if the parameters are chosen correctly. The choice is usually based on judgement and knowledge of the concerned technology. A correlation is assumed between a variable product characteristic and a variable process parameter.

In the present study, a relationship is assumed between the layer thickness (process parameter) and surface roughness, dimensional accuracy (product characteristic). Layer thickness is the property which significantly affects the quality of the prototypes in RP. This is proved by the contribution at 99% level of significance.

The correlation coefficient (r) obtained from the results is 0.6608. The range of values for (r) lies between 1 and -1. The experimental value indicates a reasonably strong positive (direct) relation. Therefore, as layer thickness increases, the surface roughness increases. The correlation coefficient (r) obtained is 0.352 for dimensional value. The experimental value indicates moderate positive (direct) relation. Therefore, as layer thickness increases, the dimensional value increases moderately.

VI. CONCLUSIONS

Process parameters in FDM process related to some important properties (i.e. surface quality and dimensional accuracy) of parts fabricated on FDM Prodigy Plus machine were investigated in this paper. From the design of experiments and ANOVA analysis it was found that layer thickness and road width affect the surface quality and part accuracy greatly. Raster angle has little effect. But air gap has more effect on dimensional accuracy and little effect on surface quality. Also the interactions between layer thickness and raster angle did not have much influence on the properties (i.e. surface finish and dimensional accuracy). The significance of layer thickness is further strengthened by the correlation analysis, which indicates a strong direct relationship with surface roughness (*i.e.*, 0.6608) and moderate relationship with dimensional value (*i.e.*, 0.352).

According to the S/N ratio following build rules are obtained from this study.

1. Use small layer thickness to increase both surface quality and dimensional accuracy.
2. Large bead width increases surface quality and moderate bead width increases dimensional accuracy.
3. Consider the effect of raster angle on part accuracy and surface quality.
4. A negative air gap can degrade surface quality and dimensional tolerances.

By applying these build rules, the surface quality and dimensional accuracy of FDM parts can be improved.

VII. SCOPE OF FUTURE WORK

In this present work only certain process parameters are considered, which affect the surface and dimensional accuracy of the components produced in FDM process assuming the other parameters at constant levels. Taking other parameters also into consideration and there by optimizing the process parameters can extend this work. Further in addition to surface quality and dimensional accuracy as quality characteristics, many other quality characteristics like production time, mechanical properties, thermal properties, product and process cost can also be into consideration for analysis.

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