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EVALUATION OF SURFACE FINISH, FORM AND DIMENSIONAL ACCURACY OF 3DP RAPID PROTOTYPES

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Abstract: Three Dimensional Printing (3DP) is one among the Rapid Prototyping (RP) techniques that is evolving towards Rapid Manufacturing (RM). Speed and accuracy are the functional requirements of an RP system. The prototype quality is evaluated by surface finish, dimensional and form accuracy obtained from RP process. There is lack of published data dealing with influence of process parameters on prototype quality in 3DP process. The experiment design was made using Taguchi orthogonal array and a evaluation model was built for each experimental run. Using a 3-D coordinate measuring machine and surface profilometer, a series of measurements in evaluating the 3DP parts quality has been conducted and nonlinear regression model was developed to find the functional relationships between the response variables and process parameters of 3DP. SEM images were taken on 3DP models to study surface topography. The optimal setups of 3DP process parameters for obtaining better prototype quality is proposed.
Keywords: Three Dimensional Printing; Nonlinear regression; SEM; Taguchi method.

1. INTRODUCTION

Solid Freeform Fabrication (SFF) processes build parts directly from computer models. These models may originate from sampled volumetric data or solid models of parts designed within a CAD system (Cho et al., 2003). A relatively new technique Three Dimensional Printing (3DP) developed by Massachusetts Institute of Technology works on the principle of ink-jet printing. A binder solution is locally applied on a powder layer by an ink-jet print head, causing the powder particles to bind to one another and to the printed cross-section one level below. This process is repeated until the entire part is printed (Melcher et al., 2006). The application of 3DP include pattern making for investment and vacuum casting, design aids for tooling application, prototyping of implants, reconstructive surgery aids etc. Hence for applications such as fit and function, pattern making or tooling for a variety of moulding and forming processes, the prototype quality characteristics such as surface finish (for aesthetic appearance), dimensional and form accuracy of prototypes obtained from 3DP is of prime importance (Dimitrov et al., 2006). The prototype quality is affected by process parameters of RP process. Studies have been conducted to improve part accuracy in several other RP process such as Stereolithography, RTV silicone rubber molding (Zhou et al., 2000) and (Rahmati et al., 2007).There is a lack of published data regarding 3DP process. This work is aimed towards finding the influence of process parameters on prototype quality obtained in 3DP process and will be beneficial for the designer to judiciously select the process parameters to obtain quality prototypes.

2. OBJECTIVE OF THIS STUDY

The objectives of this research is to conduct a detailed experimental study and to search for interrelationships between the 3DP product quality characteristics and the machine parameter setup using Taguchi experimental design, and find the optimal set up of process parameter setup to obtain better prototype quality in 3DP process.

3. TAGUCHI PARAMETER DESIGN

The objective of Taguchi parameter design is to optimize the settings of process parameter values for improving performance characteristics and to identify the product parameter values under the optimal process parameter values. It is expected that the optimal process parameter values obtained from the parameter design are insensitive to variation of environmental conditions and noise factors. Parameter design is used to dampen the effect of noise (reduce variance) by choosing the proper level for control factors (Ross 1996). S/N ratio is an objective index to measure the stability of quality. Different S/N ratios have to be chosen depending on the goal of your experiment. If S/N ratio is larger, the quality of experiment becomes nicer with this combination of factors and level setup. The different S/N ratios used are given below.

(a) Smaller the better characteristic (S.B.)

If the characteristic of the quality is smaller, the target extreme value will be zero.

$$S/N = -10 \log \left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad \ldots\ldots\ldots (1)$$

Where, y_i is the export (output) value.

(b) Bigger the better characteristic (B.B.)

If the characteristic of the quality is larger, and the target extreme value will be unlimited.

$$S/N = -10 \log \left[\frac{1}{n}\sum_{i=1}^{n} 1/y_i^2\right] \quad \ldots\ldots\ldots (2)$$

(c) Nominal the better characteristic (N.B.)

The characteristic of the quality is a target value,

$$S/N = 10 \log [u^2 / \sigma^2] \quad \ldots\ldots.. (3)$$

Where, u is the mean of output values (yi) and σ is the standard deviation of output values. Irrespective of the quality characteristic that is analyzed, the higher the S/N ratio the better is the quality characteristic.

4. EXPERIMENTAL DESIGN

Through a comprehensive literature survey the identified control factors to be used in this study are layer thickness, binder saturation –shell, binder saturation-core and build orientation apart from other parameters (Yao & Tseng 2002). Experiments were carried using Zcorp Spectrum510 3D printer. A plaster based powder (ZP102) and binder (Zb56) was used to make 3DP models. The control factors and their levels for ZP102 powder to be used in this study are shown in table 3.1. To select an appropriate orthogonal array for experiments, the total degrees of freedom need to be computed. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters (Nian et al., 1999). The degrees of freedom computed for the parameters used in this study were found to be 8. Hence L_{18} orthogonal array was chosen for designing the experiment layout and is shown in Table 3.2.

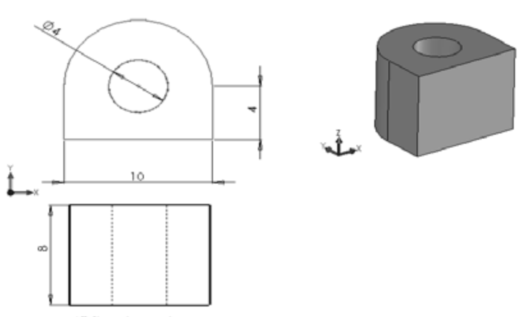

Figure 3.1: Evaluation model

The evaluation model used in this study is shown in figure 3.1. The response variables considered in this study are average surface roughness (R_a) on upper surface of evaluation model, model thickness, hole diameter, circularity and cylindricity of hole and flatness of the upper surface of evaluation model.

5. OBSERVATIONS AND CALCULATIONS

A Surtronic surface profilometer was used to measure the average surface roughness (R_a) on upper surface of each model. The R_a values were obtained at 0.25mm cutoff value twice for each test run and were recorded. The dimensional parameters such as model thickness (T_1), hole diameter (D_1), form parameters such as circularity (C_1), cylindricity (C_2) of hole and flatness (F_1) of upper surface were measured using Brown & Sharpe Co-ordinate Measuring Machine (CMM) and recorded. Incase of dimensional parameters, positive dimensional errors were observed in case of model thickness (T_1) and negative dimensional errors in case of hole diameter (D_1). The R_a values obtained from experimental runs were found in the range of 4.2 µm to 12.8 µm with average being 8.15 µm. The S/N ratio for T_1 and D_1 was calculated using equation 3 and for R_a, C_1, C_2 and F_1 using equation 1.

Table 3.1 Experimental Factors and their levels

Factors	Levels		
	1	2	3
Layer thickness in mm - A	0.0889	0.1016	-
Saturation value (shell) - B	1	0.75	0.5
Saturation value (core) - C	1	0.75	0.5
Orientation in degrees - D	0	45	90

Table 3.2 L_{18} Orthogonal Array used in this study

Exp. No.	Experimental Factors			
	A	B	C	D
1	0.0889	1	1	0
2	0.0889	1	0.75	45
3	0.0889	1	0.50	90
4	0.0889	0.75	1	0
5	0.0889	0.75	0.75	45
6	0.0889	0.75	0.50	90
7	0.0889	0.50	1	45
8	0.0889	0.50	0.75	90
9	0.0889	0.50	0.50	0
10	0.1016	1	1	90
11	0.1016	1	0.75	0
12	0.1016	1	0.50	45
13	0.1016	0.75	1	45
14	0.1016	0.75	0.75	90
15	0.1016	0.75	0.50	0
16	0.1016	0.50	1	90
17	0.1016	0.50	0.75	0
18	0.1016	0.50	0.50	45

Table 4.1 Measured values of Response variables

Exp No.	R_a		C_1		C_2		F_1		T_1		D_1	
	Mean R_a (µm)	S/N ratio (dB)	C_1 (mm)	S/N ratio (dB)	C_2 (mm)	S/N ratio (dB)	F_1 (mm)	S/N ratio (dB)	T_1 (mm)	S/N ratio (dB)	D_1 (mm)	S/N ratio (dB)
1	6	-15.56	0.05	25.35	0.071	22.97	0.071	22.97	8.251	51.137	3.381	41.334
2	5.15	-14.24	0.059	24.58	0.123	18.20	0.04	27.96	8.226	63.351	3.082	37.668
3	5.2	-14.32	0.12	18.42	0.17	15.39	0.059	24.58	8.283	50.507	3.329	39.832
4	10.4	-20.34	0.045	26.94	0.101	19.91	0.083	21.62	8.447	48.608	3.694	43.234
5	4.2	-12.46	0.038	28.40	0.098	20.18	0.057	24.88	8.245	49.223	3.494	42.511
6	8.4	-18.49	0.11	19.17	0.094	20.54	0.11	19.17	8.237	44.491	3.368	42.432
7	8.5	-18.59	0.053	25.51	0.152	16.36	0.122	18.27	8.227	54.697	3.081	41.658
8	9.4	-19.46	0.094	20.54	0.147	16.65	0.14	17.08	8.205	54.066	3.217	42.033
9	7.7	-17.73	0.07	23.10	0.073	22.73	0.055	25.19	8.487	40.032	2.998	41.421
10	12.6	-22.01	0.166	15.60	0.24	12.40	0.042	27.54	8.309	50.115	3.275	22.433
11	7.8	-17.84	0.051	25.85	0.203	13.85	0.159	15.97	8.326	54.096	2.877	39.320
12	7	-16.90	0.07	23.10	0.24	12.40	0.079	22.05	8.448	48.599	2.831	36.930
13	7.3	-17.27	0.073	22.73	0.101	19.91	0.09	20.92	8.351	58.935	2.997	40.721
14	12.8	-22.14	0.04	27.96	0.316	10.01	0.056	25.04	8.251	48.882	3.490	41.402
15	6.5	-16.26	0.024	32.40	0.109	19.25	0.086	21.31	8.610	38.603	3.554	41.983
16	10.5	-20.42	0.013	37.72	0.162	15.81	0.058	24.73	8.202	59.599	3.457	28.440
17	8.3	-18.38	0.046	26.74	0.084	21.51	0.123	18.20	8.343	37.192	3.461	40.925
18	8.95	-19.04	0.11	19.17	0.12	18.42	0.061	24.29	8.279	54.244	3.469	40.371
Avg	8.15	-17.85	0.07	24.63	0.146	17.58	0.082	22.32	8.318	50.354	3.281	39.1472

6. NONLINEAR REGRESSION FIT

(a) Average surface roughness (R_a)

The nonlinear regression fit developed for average surface roughness (R_a) from the experimental data is shown in equation 4. The R^2 value for developed nonlinear model is 0.9316. The average percent deviation between experimental and predicted R_a values was found to be 7.31%.

$$R_a = 6.4953 + 4696.351*A - 80.758*B+54.161*C-0.36411*D+1.872E+04*A*B -1.154E+04*A*C+84.9*A*D+6.49697*B*C+0.0653872*B*D- 0.0990313*C*D-1.178E+06*A*A-0.8769231*B*B-5.716841*C*C+0.0011423*D*D \quad (4)$$

Where, R_a = average surface roughness in µm, A = layer thickness in inch, B = saturation value- shell, C= saturation value-core and D = build orientation in degrees.

(b) Circularity (C_1)

A nonlinear regression fit was developed for circularity using the deviation data obtained from each experimental run and is shown in equation 5. The R^2 value for developed nonlinear model is 0.97. The average percent deviation between experimental and predicted circularity values was found to be 9.825%.

$$C_1 = 0.771936+62.2448*A-1.8602*B-0.95741*C+0.006805*D+209.23*A*B +6.62495*A*C -1.6157*A*D+0.57757*B*C+0.00184*B*D-0.001508*C*D-1.854E+04*A*A+0.3905*B*B +0.3931*C*C-3.612E-06*D*D \quad (5)$$

(c) Cylindricity (C_2)

A nonlinear regression model was developed for cylindricity using the experimental observations and is shown in equation 6. The R^2 value for developed nonlinear model is 0.94. The average percent deviation between experimental and predicted cylindricity deviations was found to be 9.46%.

$$C_2=-0.4437+83.386*A-1.8536*B+2.9617*C-0.01239*D+489.94*A*B-397.59*A*C-0.4368*B*C+0.0011*B*D-0.00125*C*D-2.12E+04*A*A+0.2526*B*B-0.7596*C*C+1.37E-05*D*D \quad (6)$$

(d) Flatness (F_1)

A nonlinear regression fit was developed for flatness using the deviation data obtained from each experimental run and is shown in equation 7. The R^2 value is shown in equation 7. The R^2 value for developed nonlinear model as shown in equation (7) is 0.98. The average percent deviation between experimental and predicted flatness deviations values was found to be 4%.

$$F_1 = 0.3582-8.17483*A-1.521*B+0.0127*C+0.0105*D +345.94*A*B+63.79*A*C-2.3587*A*D-0.03793 *B*C-0.00106*B*D-0.002206*C*D-20820*A*A +0.1592*B*B-0.05186*C*C+5.234E-6*D*D \quad (7)$$

(e) Model thickness (T_1)

A nonlinear regression fit was developed for flatness using the deviation data obtained from each experimental run and is shown in equation 8. The R^2 value for developed nonlinear model as shown in equation (8) is 0.92. The average percent deviation between experimental and predicted flatness deviations values was found to be 0.29%.

$$T_1 = 8.2351+102.636*A+0.6830*B-0.5082*C-0.0098*D+342.357*A*B-322.306*A*C -0.01282*A*D-0.4133*B*C+0.0032*B*D+0.00477*C*D1.003E+04*A*A -1.1429*B*B+1.108*C*C+2.458E-05*D*D \quad (8)$$

(f) Hole diameter (D_1)

A nonlinear regression fit was developed for flatness using the deviation data obtained from each experimental run and is shown in equation 9. The R^2 value for developed nonlinear model as shown in equation (9) is 0.90. The average percent deviation between experimental and predicted flatness deviations values was found to be 1.9%.

$$D_1 = -5.938-31.671*A+15.414*B+10.7721*C -0.01604*D-2844.311*A*B-3046.24*A*C-1.1983*A*D+0.78691*B*C +0.008339*B*D+0.00691*C*D+5.797E+05*A^2-3.9589 *B^2 -0.011419*C^2 +0.000131*D^2 \quad (9)$$

7. MAIN EFFECTS OF CONTROL FACTORS ON RESPONSE VARIABLES

Incase of average surface roughness, it was observed that layer thickness (A) and binder saturation value-core (C) have direct relationship with R_a, which means that increase in their parametric values would result in increase in R_a value obtained in prototypes obtained from 3DP process as shown in figure 5.1. The parameter binder saturation value-shell (B) has inverse relationship with R_a which means increase in its value would result in decrease in R_a value obtained or vice versa. Incase of build orientation low R_a value is obtained at 45^0 compared to 0^0 and 90^0. The reason behind the influence of build orientation on R_a is that it affects the stacking of layers on top of each other during building of prototypes. At lower angles the adjacent layers are offset by a greater distance, thus resulting in coarser surfaces as shown in Figure 5.2 (Bharath et al., 2000).

The surface topology of experimentation models observed with high and low R_a were analyzed using Scanning Electron Microscope (SEM). Incase of high R_a model, there are large number of pores seen than that in low R_a experimental model as shown in figure 5.3a and 5.3b. The wide number of pores present abundant on surface of (A2 B2 C2 D3) model had lead to higher R_a value than that in (A1 B2 C2 D2) model.

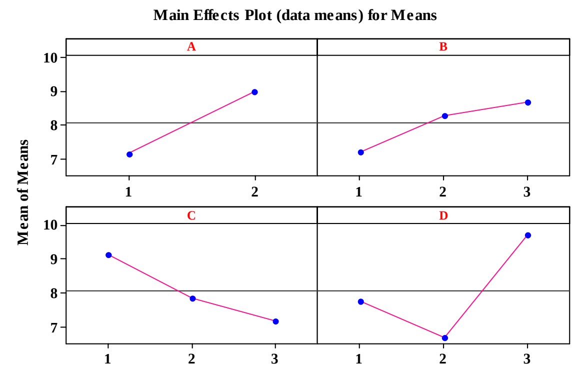

Figure 5.1: Effect of control factors on R_a

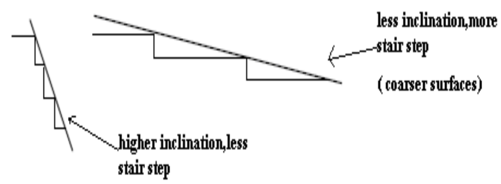

Figure 5.2: Effect of build orientation on R_a

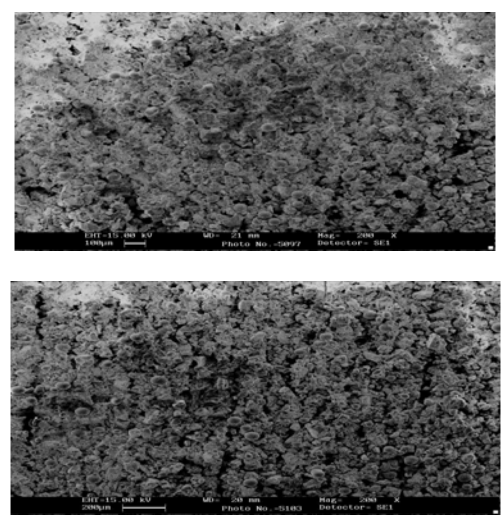

Figure 5.3: Surface topography of 3DP models a) model (A1 B2 C2 D2) with less R_a b) model (A2 B2 C2 D3) with high R_a

From the main effect plot of control factors on circularity as shown in figure 5.3, it is observed that layer thickness has inverse relationship with circularity, which means increase in their values, will lead to decrease in circularity deviations or vice versa. Build orientation has direct relationship with circularity deviations, which means increase in its value will increase the circularity deviations or vice versa. Incase of binder saturation – shell and core, minimum deviations in circularity is observed at 0.5 ratio of binder to powder. Incase of build orientation 0^o provides better circularity (less deviation) than compared to those obtained at 45^o and 90^o. At 90^o circularity deviations are higher due to inherent layer stacking as the hole in evaluation model is built in z direction (layer addition direction in 3DP machine).

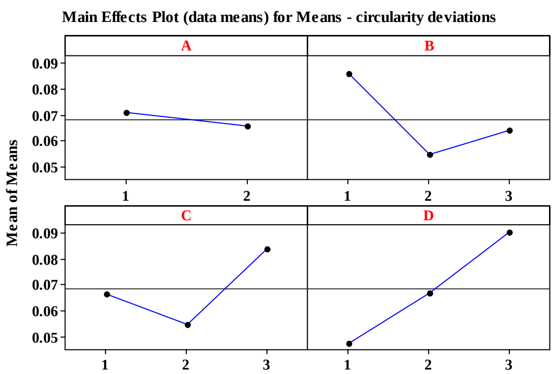

Figure 5.3: Effect of control factors on circularity

Incase of effect of control factors on cylindricity as shown in 5.4, it is observed that layer thickness, build orientation and binder saturation-shell has direct relationship with cylindricity deviations, which means increase in their respective values, will increase in their cylindricity deviations.

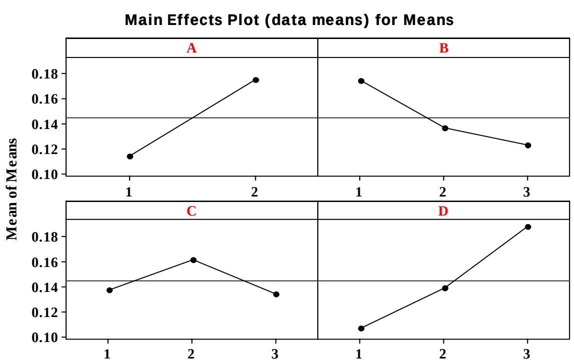

Figure 5.4: Effect of control factors on cylindricity

The influence of control factors on flatness is shown in figure 5.5. It is observed that layer thickness has direct relationship with flatness, which means increase in its value will lead to increase in flatness or vice versa. Build orientation also has inverse relationship with flatness deviations, but has low flatness deviations at 45^0 is observed than at other build angles. Incase of binder saturation–shell, minimum deviations in flatness is observed at value of 1and it shows a inverse relationship with flatness. Incase of binder saturation–core, minimum deviations in flatness is observed at 0.5 value.

Incase of model thickness (T_1) layer thickness has direct relationship with associated vertical dimension (thickness) of the model, which means if layer thickness is higher the deviation between the obtained and nominal thickness of model is also higher. Thus at lower layer thickness value (0.0889 mm) the mean model thickness values obtained have less deviation from nominal value of 8mm as shown in figure 5.6.Incase of build orientation, it has negative sign of relationship with vertical dimension (thickness). From figure 5.6, it is observed that average model thickness obtained at 90^o has less deviation from its nominal value. Thus at 90^o build orientation with respect to this experiment the vertical dimension is built in x-y plane where accuracy of machine is high than that in built direction. The stacking effect is observed in those dimensions that are built in build direction of 3DP machine and in inclined direction.

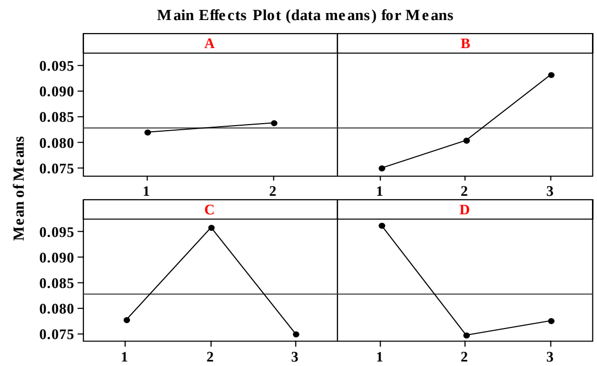

Figure 5.5: Effect of control factors on flatness

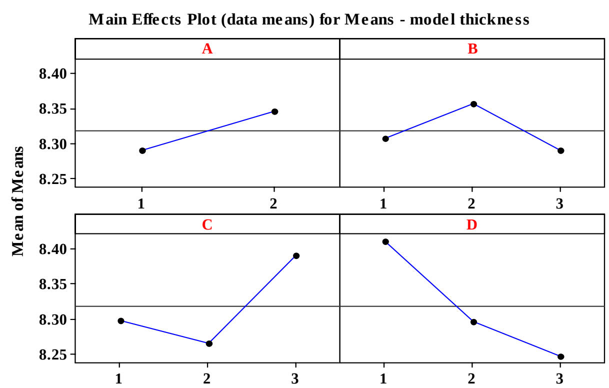

Figure 5.6: Effect of control factors on model thickness

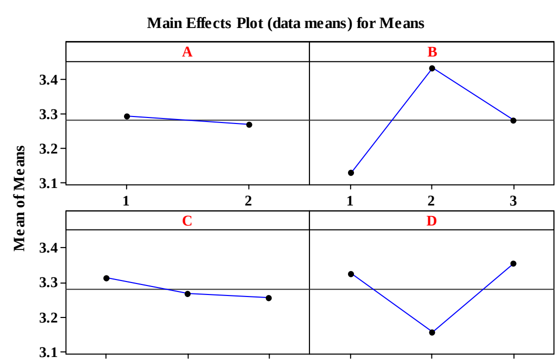

Figure 5.7: Effect of control factors on hole diameter

Analyzing Figure 5.7, it was found that layer thickness has inverse relationship with hole dimension which means increase in its value will lead to decrease in hole dimension value or vice versa. Thus at 0.0889mm layer thickness, the mean value of hole diameter obtained is nearer to its nominal value of 4mm. Binder saturation – core has direct relationship with hole dimension which means increase in its value will lead to increase in hole dimension value or vice versa. Incase of build orientation, at 0^0 and 90^0, the mean hole diameter is nearer to nominal hole diameter of 4mm than that obtained at 45^0 as it can be seen from the main effect plot as shown in Figure5.7.

8. OPTIMAL SET OF PROCESS PARAMETERS FOR RESPONSE VARIABLES

The optimal set of process parameters was obtained for each response characteristic discussed in this study using S/N ratio analysis and is shown in Table 6.1.

Table 6.1: Optimal set of process parameters

No.	Response Variable	Optimum settings
1	Average surface roughness	A1 B1 C3 D2
2	Model thickness	A1 B1 C1 D1
3	Hole diameter	A1 B2 C2 D1
4	Circularity	A2 B2 C2 D1
5	Cylindricity	A1 B3 C3 D1
6	Flatness	A1 B1 C3 D2

9. CONCLUSION

Build Orientation is the main factor influencing the surface finish, dimensional and form accuracy obtained in 3DP process. It is observed that to obtain a cylindrical feature at the best in 3DP process; it should be oriented in such a way that its axis is parallel to build direction in machine. Surface finish obtained at higher build direction is poorer due to adverse effect of stacking of layers as at higher build angle the vertical co-ordinate distance of slope between two adjacent layers is high. At lower build angle the horizontal distance between adjacent layers is high, hence a compromise between vertical and horizontal distance is attained at 45^o leading to R_a value or better surface finish in 3DP process. From the SEM analysis of model with higher R_a value, more number of pores was observed on its surface than that in least R_a value model.

Incase of model thickness observed in experimental models, positive dimensional errors were observed Incase of hole diameter, negative errors were observed which means measured diameter value were less than the nominal value. Both of these effects were due to hygroscopic effect of powder used in the 3D Printing process. Incase of critical linear dimension to be obtained in the 3DP models, it should be built in such a way that it is not parallel to build direction of machine (z-axis).The best way is to orient it in x-y plane of build direction to achieve better dimensional accuracy. 0^o build orientation provides the best quality features of 3DP prototypes except for surface finish where the influence of 45^o build orientation is felt. Overall lower value of layer thickness is found to achieve quality 3DP prototypes but a compromise has to be made in build time. The optimal setting of process parameters for surface finish and flatness are found to be same.

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