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Research Article

Parameter Optimization of ABS-M30i Parts Produced by Fused Deposition Modeling for Minimum Surface Roughness

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Abstract

Rapid Prototyping (RP) is the solid free form manufacturing process which enables the quick fabrication of physical models using three-dimensional computer aided design (CAD) data. Fused Deposition Modeling (FDM) is a solid-based rapid prototyping method that extrudes material, layer-by-layer, to build a model. Knowledge of the quality characteristics of FDM fabricated parts is vital. Quality extensively depends on process variable parameters. Hence, the Optimization of these process parameters of FDM is able to make the system more specific and repeatable and such progression can guide to use of FDM in rapid manufacturing applications rather than only producing prototypes. In order to understand this issue, this paper explains the results obtained in the experimental work on the cause of the main FDM process variable parameters namely, layer thickness (A), air gap (B), raster width (C), contour width (D), and raster orientation (E). The novel ABS- M30i biomedical material was used in this research work to build parts. Experiments were conducted using Taguchi's design of experiments with two levels for each factor. The results are analyzed statistically to determine the significant factors and their interactions.

Keywords: *Biomedical material, Fused Deposition modeling, Rapid Prototyping, Surface Roughness, Taguchi's Method*.

1. Introduction

Rapid prototyping (RP) is a manufacturing technology that fabricates 3D physical models directly from 2D CAD data using a layered manufacturing (LM) process that stacks and bonds thin layers in one direction. Stereo lithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), and laminated object manufacturing (LOM) is representative RP technologies (Chua, et al, 1999),(Levy, et al, 2003) . Fused Deposition Modeling (FDM) is a leading RP technology that is used for fabricating solid prototypes directly from a computer-aided design (CAD) data. Surface roughness is the key property of RP build parts. Surface finish is considered as a vital feature and parts must be prepared in line with the product finishing specifications. However, there are certain materials for which it is difficult to meet the specifications, thus an optimum and achievable choice of material and application conditions is essential. Consequently, the operating conditions that optimally suit a material must be employed and their characteristics have to be taken into account. The surface finish of parts obtained through these manufacturing processes is important, especially in cases where the components are in contact with other elements or materials in their service life. For example building moulds to produce components by means of Solid Free Form Manufacturing Processes, or cases of other functional components where their surface characteristics will have a considerable effect on their mechanical properties such as fatigue, wear, and corrosion. Therefore, it is important to have prior knowledge, by means of conceptual models, of the manufacturing process parameters that allow the user to predict the surface finish of manufactured prototypes (Ahn, et al, 2004), (Reeves, et al, 1997).

2. Prior Art

Fused Deposition Modeling (FDM) is a leading RP technology that is used for fabricating solid prototypes in various materials directly from a computer-aided design (CAD) data. The quality and the strength of the FDM build parts are dependent essentially on the process parameters. The FDM systems available in the market are different in their build speed, build volume, range of parameter settings and build materials (Masood, et al, 2010). In order to understand the performance and the behavior of FDM build parts, the influence of the process parameters on outcome quality of the build parts must be studied. Earlier studies (Mahapatra, et al, 2009), (Ahn, et al, 2002) have reported that FDM parameters such as layer

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thickness, air gap, raster width, and raster orientation were significantly impacting the quality characteristics of build parts.

In relevant empirical studies, parametric optimization was used to develop the quality characteristics of FDM parts or the process performance where the number of FDM process parameters were studied and optimized. For instance, (Lee, et al, 2005) and (Laeng, et al, 2006) investigated the elasticity performance of ABS material. Similarly, (Ang, et al, 2006) and (Es-said, et al, 2000) investigated the tensile strength of FDM parts. (Anitha, et al, 2001) optimized the FDM process parameters improving the surface roughness of build parts, while (Gregorian, et al., 2001), (Sood, et al., 2010) have looked into the dimensional accuracy of FDM parts. These previous studies investigated a single outcome quality response while some studies were done in parametric optimization by investigating multiple quality objectives responses, such as (Wang, et al., 2007), (Kumar, et al., 2004). They suggested that building a functional part is attributed to various loading environments in practice. Consequently, process parameters require to be studied in such a way that they are collectively optimized simultaneously, rather than optimize a single quality response.

In this research, multi-objective experimentation has been implemented where the Surface roughness of FDM build parts was investigated. Five parameters were optimized; layer thickness (A), air gap (B), raster width (C), contour width (D), and raster orientation (E).

3. TaguchiMethod

The Taguchi design of experiment method was used in this project to estimate the relative role of process parameters on surface quality of FDM parts. Taguchi method uses a unique set of arrays called orthogonal arrays which specify the way of conducting the minimum number of experiments, which would give the full information of all factors that affect the performance parameters. In this study, Full factor experiment orthogonal array design of L32 (two levels-five factors) has been selected initially according to the number of FDM variable parameters and number of settings or levels. The preferred process parameters distressing the quality of FDM parts and their levels are given in Table 1. Table 2 shows the L32 array.

Table 1 Variable Parameters and their Selected Low and High Levels

Variable parameter	Low level	High level
Layer thickness (A)	0.254	0.353
Air gap (B)	0	-0.01
Raster width (C)	0.508	0.8
Contour width (D)	0.508	0.8
Raster orientation (E)	$45^o/-45^o$	$45^o/90^o$

Table 2 Full Factor Design includes 32 experimentation runs

Runs	A	B	C	D	E
1	1	1	1	1	1
2	1	1	1	1	2
3	1	1	1	2	1
4	1	1	1	2	2
5	1	1	2	1	1
6	1	1	2	1	2
7	1	1	2	2	1
8	1	1	2	2	2
9	1	2	1	1	1
10	1	2	1	1	2
11	1	2	1	2	1
12	1	2	1	2	2
13	1	2	2	1	1
14	1	2	2	1	2
15	1	2	2	2	1
16	1	2	2	2	2
17	2	1	1	1	1
18	2	1	1	1	2
19	2	1	1	2	1
20	2	1	1	2	2
21	2	1	2	1	1
22	2	1	2	1	2
23	2	1	2	2	1
24	2	1	2	2	2
25	2	2	1	1	1
26	2	2	1	1	1
27	1	2	1	2	1
28	1	2	1	2	2
29	1	2	2	1	1
30	2	2	2	1	2
31	2	2	2	2	1
32	2	2	2	2	2

4. Experimental Procedure

A trial run was performed in which a series of samples were built on the FDM FORTUS 400mc using ABS M30i material. FDM FORTUS 400mc by Stratasys was used to produce the specimens. The machine is equipped with Insight software that assists the user to adjust the variable parameters in building part specification. Principally, the FDM variables are considered as four groups of operating parameters, as follows; FDM build specification, FDM environment/machine, and material specification.

The full factor experiment was obtained to develop the experimentation plan for five parameters and two levels, considering the highest number of experimentation runs for the specified number of runs and levels in order to optimize the maximum parameters combinations. In this study, Full factor experiment orthogonal array design of L32 (two levels-five factors) has been selected initially according to the number of FDM variable parameters and number of settings or levels.

The dimensions of the samples were selected according to ASTM specimen as shown in figure 1.

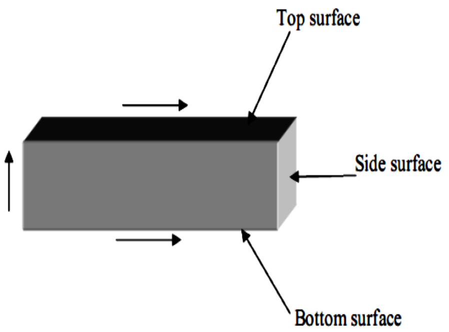


Fig.1 Test Specimen for roughness measurement (arrow show direction of measurement of roughness)

Three readings of average surface roughness (Ra) on top, bottom and left side surface is taken for specimen shown in Figure 1. Mean of these three observations is taken as representative value of respective surface roughness. For measuring surface roughness, a contact type roughness tester is used.

5. Results and Discussion

For the surface Roughness (Ra) response, figure 2 shows the distribution of the resulting data appears to be normal but cyclic in nature from minimum to maximum and then minimum. Main effects and regression analysis will be used to explain this phenomenon. From figure 2 it can be seen that the Ra value is lower in some runs and higher in others, which means that the combination of parameters in each run has impact on the surface roughness characteristics for the resulted FDM parts.

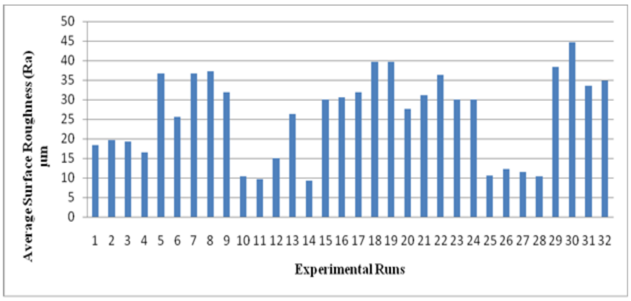
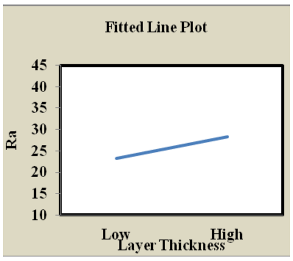


Fig.2 The average values of 32 parts

5.1 Fitted Line Plot

Fitted line plot by regression analysis is used to examine the relationship between the response variable (Ra) and the predictor variable (low level and high level of FDM variable parameters). The method used to draw the line is called the least-squares criterion. The more the line is inclined, the more the parameter impacts the response by its low and high level.

Using the line in figure 3, it can be evaluated that the layer thickness affects the response value (Ra) due to the inclined fitted line. Also it can be seen that layer thickness at low level attained the lower Ra value.



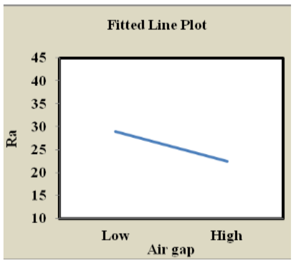
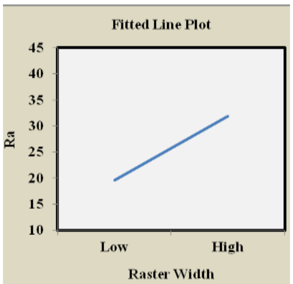


Fig.3 Fitted Line Plot for Layer thickness parameter

Fig.4 Fitted Line Plot for Air gap parameter

Figure 4 shows the inclined fitted line for air gap parameter. It can also be seen that it affects the response value. It shows that the optimum setting is at high level. This means that the high level attained lower response mean.

Figure 5 shows the inclined fitted line for raster width parameter which shows that raster width parameter affects the response value. Also it shows optimum setting for raster width at low level where it has attained lower response mean in comparison to high level. These results may provide explanation that there are other parameters settings that have led to the reduction of the Ra value in run number 14 although raster width has been set to high level.



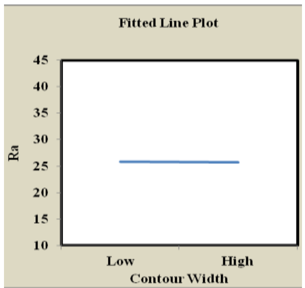


Fig.5 Fitted Line Plot for raster Width parameter

Fig.6 Fitted Line Plot for contour width parameter

Fitted line plot of contour width and raster orientation in figure 6 and 7, indicate that the impact of low level and high level of both parameters may have equal effect on Ra. It cannot be concluded whether the experimental runs included contour width and raster orientation at low level have attained lower Ra values than at low level.

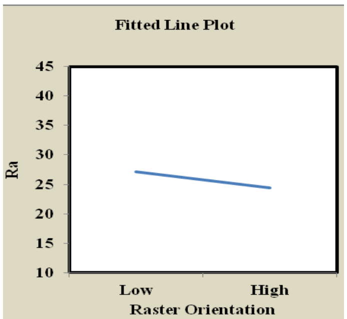


Fig.7 Fitted Line Plot for Raster Orientation parameter

5.2 ANOVA Analysis

Table 3 ANOVA shows that only air gap and raster width are significant hence they have P-value less than α (α = 0.05), also they have the highest F factor but no interaction is significant. The Adj MS and Adj SS indicate to the delta variation or the influence by applying low and high level of each process parameter, these values will be used to compare the influence of parameters on each response characteristic.

Table 3 ANNOVA table for Surface Roughness Ra

Source	DF	Seq SS	ADj SS	ADj MS	F	P
A	1	249.7	249.7	249.7	2.88	0.109
B	1	427.7	427.7	427.7	4.93	0.041
C	1	1096	1096	1096	12.6	0.003
D	1	3.35	3.35	3.35	0.04	0.847
E	1	39.6	39.6	39.6	0.46	0.508
A*B	1	17.49	17.49	17.49	0.2	0.659
A*C	1	0.37	0.37	0.37	0	0.949
A*D	1	60.78	60.78	60.78	0.7	0.415
A*E	1	90.12	90.12	90.12	1.04	0.323
B*C	1	221.6	221.6	221.6	2.55	0.13
B*D	1	0.88	0.88	0.88	0.01	0.921
B*E	1	5.04	5.04	5.04	0.06	0.813
C*D	1	49.15	49.15	49.15	0.57	0.463
C*E	1	1.61	1.61	1.61	0.02	0.893
D*E	1	11.21	11.21	11.21	0.13	0.724
Error	16	1388.2	1388.2	86.77		
Total	31	3663.2				

5.3 Regression Analysis

Regression analysis table was used to determine the equation of each parameter in linear relationship to Ra response. Also it gives interpretation of the influence of each parameter settings as shown in table 4. Analysis of variance (ANOVA) and regression analysis use the P-values to determine the significant of the FDM parameter or the parameters interaction that affect the Ra response. These methods of analysis are use hypothesis test according to the probability or P-value, hence if the P-value is below α-value, the higher the probability to reject the null hypothesis and consequently considering the parameter or the interaction as significant. The P-values in table 4 were used to measure the significant effects of FDM parameters. P-value determines the suitability of rejecting the null hypothesis in a hypothesis test. P-values range from 0 to 1. The P-value is the probability of determining a statistical testing that is able to confirm that the variation has occurred because of the parameter or interaction.

In Table 4 the FDM parameters were analyzed according to their effectiveness to the source of the response Ra. The coefficient value of each parameter provides an estimation of the influence of each parameter. Hence the absolute values of each coefficient of input parameters were compared to interpret the results.

As shown in regression analysis (table 4) raster width is significant hence its P-value is less than α test value.

Table 4 Regression Analysis versus parameters for surface roughness Ra

Predictor	Coef	SE Coef	P
Constant	15.43	10.1	0.139
A	5.587	2.98	0.072
B	-7.313	2.98	0.021
C	11.705	2.98	0.001
D	-0.648	2.98	0.83
E	-2.227	2.98	0.461

Also by looking at the regression coefficient value in table 4, it has the highest coefficient value (11.705), this indicates that raster width parameter has the highest impact on the surface quality. In addition the coefficient value for raster width parameter is a positive value, which can be interpreted that when the raster width parameter is set to high level than the surface roughness becomes higher, or in other words, the optimum setting for the raster width parameter is the low level. Also air gap is significant but less significant than raster width, hence it has P-value is (0.021) which is less than α-value test. Moreover, the negative value of coefficient means that when air gap parameter is set to high level then the surface roughness is reduced or becomes lower. In addition, the level of parameter significant can be interpreted by the absolute value of the coefficient value. Therefore, raster width (C) has the most significant at (11.705), then air gap (B) at (7.313), and then layer thickness (A) at (5.587). Similarly, table 3 shows that only air gap and raster width are significant hence they have P-value less than α, but no interaction is significant.

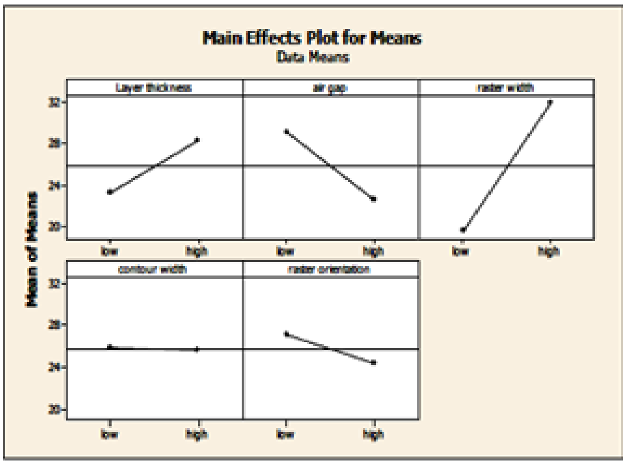


Fig.8 Main Effects Plot for Means for Surface Roughness Ra

Figure 8 shows the main effects plot for means. This plot is used to identify the most FDM parameters that affect the surface roughness response according to the response means, which is attained by each parameter level. Therefore, when the mean line is parallel to x-axis then it can be concluded that the parameter has no effect on response Ra and when the line is inclined then the parameter affects the response by its low and high level. Layer thickness, air gap and raster width potentially affect the Ra response since the mean line is inclined to x-axis. However raster orientation may have less effect on Ra, while contour width has no effect. Consequently, air gap at low level has higher average response than high level, which means that the response is less when air gap is set to higher level. Also, raster width parameter low level has less average response than high level, which means that the response is less when raster width is set to lower value, the same for layer thickness. The raster orientation may affect the response slightly, while contour width is not significant since its response line is in parallel to x-axis.

Conclusions

In this research, five FDM parameters: (A) layer thickness, (B) air gap, (C) raster width , (D) contour width , (E) raster orientation were examined at two variable settings for building test parts. Full factor design was used in this research to conduct an experimentation plan to determine the optimum parameters settings that affect the output characteristic response i.e., surface roughness (Ra). It has been found that not all FDM parameters have impact on the Surface roughness; also the FDM parameters vary in their influence on each proposed response characteristic. Air gap parameter has been proved statistically to influence the surface finish of FDM built parts, combined with layer thickness at (0.254 mm) and raster width at (0.508 mm). By applying negative air gap at (-0.01), the beads of ABS M-30i overlapped and the voids between the built beads were filled, this resulted in a smooth surface construction and a lower Ra value compared with other built parts with default settings. Hence, it has been found that the voids between the deposited layers caused a roughed surface. Building parts with thinner layers or narrower roads may reduce the surface roughness.

1) Negative air gap at (-0.01 mm) and layer thickness at (0.254 mm) or raster width at (0.508 mm) can be used to reduce surface roughness.
2) Use small layer thickness to increase Surface Quality.
3) Using the optimal part orientation is vital to reduce support material, which will lead to reduce building time and improve the surface finish.

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