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An Experimental Investigation of Effect of Process Parameters on Surface Roughness of Fused Deposition Modeling Built Parts

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Abstract **--Rapid prototyping (RP) refers to a class of technology that can automatically construct the physical models from computer aided design (CAD) data. Fused deposition modelling (FDM) is process for developing rapid prototype objects from plastic material by lying track of semi molten plastic filament on to a platform in a layer wise manner from bottom to top. The aim of this paper is to investigate the effect of process parameters on surface roughness of fused deposition modelling built parts. Response surface methodology (RSM) was used to conduct the experiments. The parameters selected for controlling the process are layer thickness, part built orientation and raster angle. Surface roughness of fused deposition modelling built parts is measured by surface roughness tester. From the results of the experiments, mathematical model have been developed to study the effect of process parameters on surface roughness.**

***Keyword—Rapid Prototyping, Fused Deposition Modeling, Response Surface Methodology*.**

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1. INTRODUCTION

Rapid prototyping 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 RP process is capable of building parts of any complicated geometry in least possible time without incurring extra cost due to absence of tooling [1]. Another advantage with rapid prototyping is to produce functional assemblies by consolidating sub assemblies into a single unit at the computer aided design stage and thus reduces part counts, handling time and storage requirement and avoids mating and fit problem. Due to compatibility of presently available materials with RP technologies full scale application of RP is not possible. To overcome this limitation, there are generally two approaches for the full scale application of RP process, one is to use of new materials with superior properties and another is to suitably adjust the process parameters for part fabrication for maximum improvement in part properties. Many of researchers have devoted towards the second approach. Less researchers work on polycarbonate material therefore, polycarbonate material has been selected for experimental investigation on FDM. Literature presents that surface roughness is the function of various process related parameters and can be significantly improved with proper adjustment. The present study focus on assessment of surface roughness of part fabricated using fused deposition modelling (FDM) technology. As the relation between surface roughness and process parameters is difficult to establish, attempt has been made to derive the empirical model between the processing parameters and surface roughness using response surface methodology. In addition, effect of each process parameter on surface roughness is analysed.

2. LITERATURE REVIEW

R. Anitha et al.[2] have assessed of influence of three process parameters with three levels such as layer thickness in mm (0.1778, 0.254, 0.3556), road width in mm (0.537, 0.622, 0.706) and deposition speed in mm (100, 150, 200) on FDM built parts with the use of Taguchi method. The objective of the study to analyses the effect of process variables on the surface roughness of the parts produced by the FDM process. The result shows that without pooling the layer thickness is effective to 49.37% at 95% level of significance. But with pooling, layer thickness is effective to 51.57% at 99% level of significance. While the other factors, road width and speed, contribute to 15.57% and 15.83% at 99% level of significance respectively. It has been revealed though correlation analysis that inverse relation exist between layer thickness and surface roughness. According to S/N analysis, the layer thickness is most effective when it is at 0.3556mm, the road width at 0.537mm and the speed of deposition at 200mm.

R. I. Campbell et al.[3] have identified that for several RP processes, the surface roughness varies across a full range of surface angles. It has been compared the surface profiles of test samples made by various RP processes like SLA (SLA-350), Thermo Jet (Actua 2100), FDM (FDM 16500), LOM (LOM 1015) and 3D Printer (Z 402) with roughness prediction model proposed by Reeves and Cobb equation $Ra=Lt\sin\theta/4\tan\theta$ where, Ra is average roughness, Lt is layer thickness and θ is the angle between the surface normal and vertical direction. It has been shown that surface roughness can be well predicted in a wide range of angles for majority of systems in SLS, Thermo Jet, FDM and LOM. Experimental works revealed that for some systems the stair-stepping effect does not appear to be the main factor in determining surface roughness. Above equation estimates higher values of surface roughness for upward facing surface in parts built on Thermo Jet, most surfaces of FDM and 3D printer built parts. It have been concluded that there are other process parameters apart from layer thickness that influence surface roughness.

Pulak M. Pandey et al.[4] have presented a semi-empirical model for evaluation of surface roughness of a layered manufactured parts by FDM by considering layer thickness and build orientation as process variables. FDM part is fabricated with 0.254mm layer thickness, 270^{o} model temperature, 265^{o} support structure temperature, 0.511mm road width and zero air gap to carry out surface roughness study. Also, present the surface roughness resulting due to staircase effect in rapid prototyped part is one of the major problem. It has been done that experiments a hybrid FDM system in which material deposition in a layer-by-layer and machining of edges by hot cutter simultaneously. Experiments are concluded that the proposed machining method is able to produce surface finish of the order of 0.3µm with 87% confidence level. This machining process given a key for development of a hybrid rapid prototyping system, which will have features of both layer-by-layer machining and deposition simultaneously, in order to achieve improved surface finish and functionality of RP parts.

K. Thrimurthulu et al.[5] has worked towards obtaining an optimum part deposition orientation for fused deposition modeling process for enhancing part surface finish and reducing build time. Model has been developed for evaluation of average part surface roughness and build time. Also, assumed a parabolic build edges for FDM build part and uses the concept of minimum surface roughness measured in terms of layer thickness and part built orientation for determining the optimum orientation of part. Both build time and average part surface roughness are two contradicting objectives, which are minimized by minimization of their weighted sum. The effect of support structure is considered in the evaluation of two objectives. Adaptive slicing have been done for determine optimum part deposition orientation.

L. M. Galantucci et al.[6] investigated the link between the FDM process parameters and the surface aspect of prototypes, studying a chemical method to improve surface finish of the products. Experimental activity has been carried out in two phases one is specimen manufacturing and other is chemical finishing. Full factorial experimental plan has been performed and Process parameters are with two levels are tip size in mm (0.254, 0.305), the raster width in mm (0.305, 0.709) and the slice height in mm (0.178, 0.254). It has been carried out the chemical treatment to FDM ABS part by immersing them in a volume of 90% di-methyl-ketone and 10% water for 300s. The results shows that the chemical treatment cuts away material but the subtracted ABS is balanced by the absorption of the solution and the roughness of the specimens has been improved considerably by using the chemical process as compared to untreated specimen. This proposed chemical treatment is economic, fast and easy to use.

Daekeon Ahn et al.[7] represented a new approach to model surface roughness in fused deposition modeling. Theoretical model have been done for prediction of surface roughness involving surface angle, layer thickness and overlap interval between adjacent layers for FDM built parts using filament of elliptical cross-section. FDM test parts fabricated from ABS material to verify the proposed surface roughness expression. By comparison between the measured data and computed values, the validity of the proposed expression was proved. Also, the effects of surface angle, layer thickness, cross-sectional shape of the filament and overlap interval on surface roughness where analyzed and evaluated. Results shows that an elaborate prediction of the surface roughness of the FDM parts can be performed with presented surface roughness expression.

3. Methodology of Investigation

3.1 Response Surface Methodology (RSM)

Response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving and optimizing processes [8]. With this technique, the effect of two or more factors on quality criteria can be investigated and optimum values are obtained. In RSM design there should be at least three levels for each factor. For present study, factors and levels of process parameters are shown in Table 1.

Table 1 Factor and Levels

Coded Factors	**Process Parameter**	**Level**		
		(-1)	**0**	**(1)**
A	Layer Thickness (mm)	0.1778	0.254	0.3302
B	Part Build Orientation (degree)	0	15	30
C	Raster Angle (degree)	0	30	60

RSM also quantifies relationships among one or more measured responses and the vital input factors. The version 16 of the MINITAB software was used to develop the experimental plan for RSM.

3.2 Central Composite Design (CCD)

The first requirement for RSM involves the design of experiments to achieve adequate and reliable measurement of the response of interest. To meet this requirement, an

IJERT

appropriate experimental design technique has to be employed. The experimental design techniques commonly used for process analysis and modelling are the full factorial, partial factorial and central composite designs. A full factorial design requires at least three levels per variable to estimate the coefficients of the quadratic terms in the response model. A partial factorial design requires fewer experiments than the full factorial design. However, the former is particularly useful if certain variables are already known to show no interaction. An effective alternative to factorial design is central composite design, requires many fewer tests than the full factorial design and has been shown to be sufficient to describe the majority of steady-state process responses [9]. Hence in this study, it was decided to use CCD to design the experiments. Hence, the total number of tests required for the three independent variables is $2^3 + 2x3 + 6 = 20$.

3.3 Factors and Levels

In this present study, three process parameters are taken. Layer thickness, part build orientation and raster angle are the process parameters. As per central composite design experimental plan is shown in Table 2.

Table 2 CCD Experimental Plan

Sr. No.	Layer Thickness	Part Build Orientation	Raster Angle
1	0.2540	15	0
2	0.1778	30	60
3	0.1778	15	30
4	0.1778	0	60
5	0.2540	15	30
6	0.3302	0	0
7	0.2540	30	30
8	0.2540	15	30
9	0.3302	0	60
10	0.2540	15	30
11	0.2540	15	30
12	0.3302	30	0
13	0.1778	30	0
14	0.2540	0	30
15	0.2540	15	60
16	0.2540	15	30
17	0.2540	15	30
18	0.3302	15	30
19	0.1778	0	0
20	0.3302	30	60

4 EXPERIMENTAL WORK

4.1 Experimental Procedure

Specimen has been prepared on Fused deposition modeling 360mc machine setup. And surface roughness measured on this specimen with SURFEST SJ-210 as shown in Figure 1. Average of two readings taken as surface roughness reading.

Figure 1 Test Specimen

Experimental results of surface roughness are shown in Table 3.

Table 3 Experimental Results of Surface Roughness

Sr. No.	Layer Thickness in mm	Part Build Orientation in Degree	Raster Angle in Degree	Surface Roughness in µm
1	0.2540	15	0	7.27
2	0.1778	30	60	12.176
3	0.1778	15	30	7.547
4	0.1778	0	60	0.897
5	0.2540	15	30	7.85
6	0.3302	0	0	3.35
7	0.2540	30	30	14.84
8	0.2540	15	30	7.9
9	0.3302	0	60	3.2
10	0.2540	15	30	7.95
11	0.2540	15	30	7.93
12	0.3302	30	0	9.5
13	0.1778	30	0	11.497
14	0.2540	0	30	4.234
15	0.2540	15	60	9.53
16	0.2540	15	30	8.1
17	0.2540	15	30	8.0
18	0.3302	15	30	7.977
19	0.1778	0	0	0.52
20	0.3302	30	60	14.7

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5 Results and Discussion

5.1 Analysis of Result of Surface Roughness

Analysis of variance is similar to regression in that it is used to investigate and model the relationship between a response variable and one or more independent variables. Analysis of the experimental data for surface roughness obtained from central composite design runs is done in MINITAB R16 software using full quadratic response surface model used to determine the influence of layer thickness, part build orientation and raster angle on surface roughness [10]. Table-4 shows the estimated regression coefficients for surface roughness.

Table-4 Estimated Regression Coefficients

Term	Coef	SE Coef	T	P
Constant	-12.613	5.6138	-2.247	0.048
A	115.248	45.9594	2.508	0.031
B	0.343	0.1006	3.406	0.007
C	-0.013	0.0503	-0.252	0.806
A*A	-209.156	89.5073	-2.337	0.042
B*B	0.002	0.0023	1.079	0.306
C*C	-0.001	0.0006	-1.109	0.293
A*B	-0.504	0.2666	-1.889	0.088
A*C	0.218	0.1333	1.638	0.132
B*C	0.002	0.0007	2.319	0.043

S=0.861856 R-sq=97.44% R-sq (adj)=95.15%

In estimated regression coefficients for surface roughness, factor A, B, square term A*A and interaction B*C are important because their p value is less than 0.05. The coefficient of determination (R^2) which indicates the goodness of fit for the model here the value of R^2 =97.44% which indicate the high significance of the model. From regression analysis, a mathematical model for predicting surface roughness in terms of layer thickness, part build orientation and raster angle is developed and given below: Ra = -12.613 + 115.248A + 0.343B – 209.156(A*A) + 0.002(B*C). Analysis of variance for surface roughness is shown in Table-5.

Table-5 Analysis of Variance for Surface Roughness

Source	DF	SS	Adj MS	F	p
Regression	9	283.277	31.4753	42.37	0.000
Linear	3	265.854	5.7180	7.70	0.006
Square	3	8.784	2.9281	3.94	0.043
Interaction	3	8.639	2.8797	3.88	0.045
Residual Error	10	7.428	0.7428		
Lack of Fit	5	7.390	1.4780	195.77	0.000
Pure Error	5	0.038	0.0075		
Total	19	290.705			

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DF=degree of freedom SS=sum of square
MS=mean sum of square
The analysis of variance table summarizes the linear terms, the squared terms and the interactions. The small p-values for the interactions and the squared terms suggest the there is curvature in the response surface. In Table-5 p value of all the term is less than 0.05 therefore all term are significant.

5.2 Response Surface Analysis for Surface Roughness

Response surface plot is one of the best methods to represent the experimental data. Figure 1 shows surface plot of surface roughness for interaction of raster angle and layer thickness, when part build orientation taken as hold value.

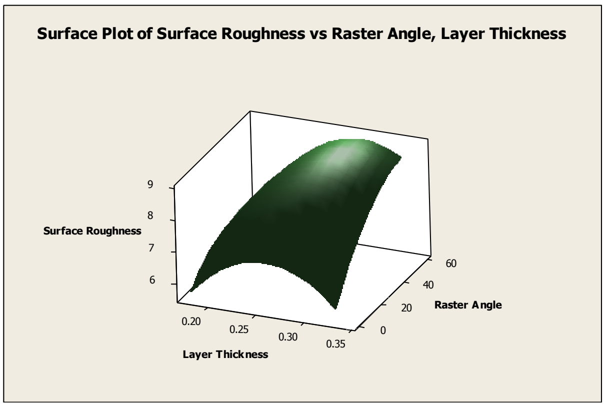

Figure 1 Surface Plot of Surface Roughness Vs Raster Angle, Layer Thickness

Surface plot in Figure 1 indicates that surface roughness increases with increase in both layer thickness and raster angle.

Figure 2 shows surface plot of surface roughness for interaction of raster angle and part build orientation, when layer thickness taken as hold value.

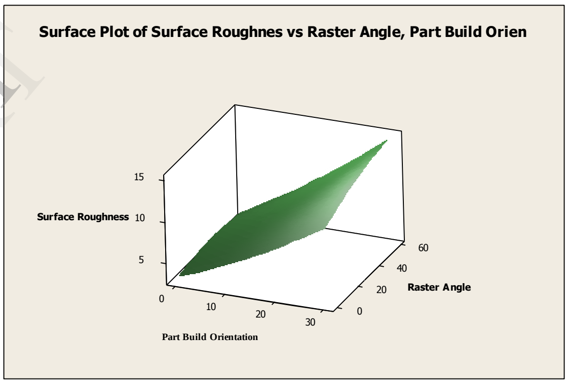

Figure 2 Surface Plot of Surface Roughness Vs Raster Angle, Part Build Orientation

Surface plot in Figure 2 indicates that surface roughness increases with increase in part build orientation but influence of raster angle on surface roughness is not significant.

Figure 3 shows surface plot of surface roughness for interaction of part build orientation and layer thickness, when raster angle taken as hold value.

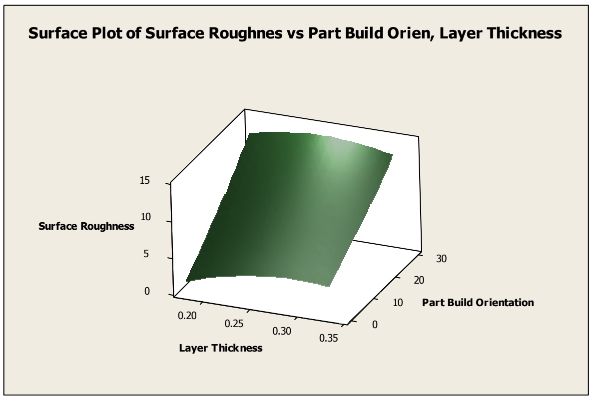

Figure 3 Surface Plot of Surface Roughness Vs part build Orientation, layer thickness

Surface plot in Figure 3 indicates that surface roughness increases with increase in both part build orientation and layer thickness

6. CONCLUSION

The effect of process parameters like layer thickness, part build orientation and raster angle on surface roughness has been studied. Experiments were conducted using response surface methodology (central composite design matrix) and mathematical model have been developed. The response plots are analysed to assess influence of each factor and their interaction on surface roughness. Experimental result analysis and surface plots concluded that part build orientation has the most significant effect on surface roughness followed by layer thickness. However raster angle has least significant influence on surface roughness.

IJERT

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