SENSITIVITY OF RP SURFACE FINISH TO PROCESS PARAMETER VARIATION

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Abstract

In the rapid prototyping process, surface finish is critical as it can affect the part accuracy, reduce the post processing costs and improve the functionality of the parts. This paper presents an experimental design technique for determining the optimal surface finish of a part built by the Fused Deposition Modeling (FDM) process. The design investigates the effect of the parameters; build orientation, layer thickness, road width, air gap and model temperature on the surface finish. Experiments were conducted using a fractional factorial design with two levels for each factor. The results are statistically analyzed to determine the significant factors and their interactions. The significant factors, their interactions and the optimum settings are proposed.

Introduction

Rapid Prototyping (RP) is finding applications in diverse fields in the industry today, with prototypes used for form, fit and function. Design Engineers around the world use Rapid Prototyping to pre-estimate product characteristics like shape, manufacturability and finish. Especially when it comes to manufacturing precise parts like aerospace components and parts with critical dimensions, it becomes imperative to check for surface finish. A good surface finish on the parts helps eliminate dimensional inaccuracy and costs due to subsequent post-processing of the part to attain the desired surface finish. Common surface defects include the staircase effect, chordal effect, support structure burrs and errors due to the starting and ending of deposition. Fused Deposition Modeling is a layered manufacturing process. In all layered manufacturing process, the slicing of the CAD model leaves a characteristic effect called the staircase effect on the part produced. This error cannot be eliminated, but can be scaled down by reducing the slice thickness. The chordal error is induced when STL files are generated from the CAD model. All curved surfaces in the CAD Model are approximated as a series of triangles, hence leading to a non-smooth surface. A rough solution to this problem is to do a positive offset to the surface, build the prototype and then do surface finishing operations to bring it back close to the original. This would however never result in a perfect model. It is confirmed that the surface finish problem cannot be completely eliminated. Hence one has to come up with a way to reduce the problem by a certain degree. Our hypothesis is that this can be done by careful process parameter control. This paper describes a designed experiment conducted to study the sensitivity of the surface finish to process parameters variation.

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Previous Work

Some work has been done with Design of Experiment techniques to determine the effect of process parameters on the quality of a prototype. Most of the work is related to Stereolithography (SLA) and Selective Laser Sintering (SLS) processes. Montgomery et al. [1] conducted an experiment on a SLS machine whose results conclude that layer thickness and part orientation are important and they also state that thicker layers would provide a better surface finish with a vertical orientation. Since the resulting surface finish due to layer thickness and orientation is a direct effect of the layered manufacturing technique, this result will hold good for other LM processes. Montgomery et al. [2] show that experimental design techniques can be applied to a real industrial product and process development problem. Armillotta et al. [3] conducted an experimental study on the relation between surface finish and layer thickness, orientation, road width and raster angle in the Fused Deposition Modeling process. Gautham et al. [4] conducted experiments to obtain surface roughness values as a function of orientation and layer thickness and developed a decision support software which allows dynamic color-coded visualization of surface quality with respect the two build parameters. Our work describes an experimental technique that uses 2^{5-1} factorial design to study the effect of the process parameters on the surface roughness of the FDM prototypes.

Approach

As Rapid Prototyping is moving towards Rapid Manufacturing there is an increasing stress on obtaining good quality parts. Quality of a prototype includes the surface quality, the mechanical strength and dimensional accuracy among other things. Surface Finish on prototypes is becoming more and more important with more parts being used for end purposes. Surface Finish is critical not only for better functionality and look, but also for cost reduction in terms of reduced post-processing of parts (this includes sanding, filing etc.) and overall prototyping time reduction also.

Fused Deposition Modeling is a complex technology involving many different process parameters. An experimental design technique is a useful tool to improve the surface finish on a part by analyzing the effects. Surface finish is a function of a number of factors. Amongst them are Build Orientation, Layer Thickness, Road Width, Air Gap and Model Temperature. An optimal setting of these parameters involved in the build process would result in a FDM prototype with good surface quality. This paper describes an experimental design technique that can be used to set these process parameters at optimal levels. An outline of the procedure is shown below.

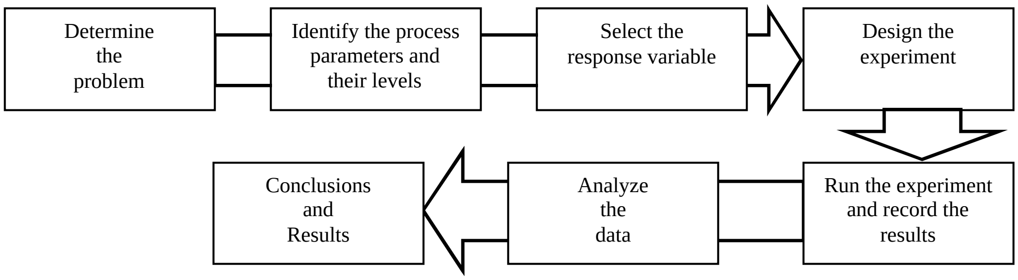

Figure 1Designed Experiment Sequence

The layer thickness determines the height of the stair-step. The lesser the layer thickness the lesser the stair-step produced on the prototype. For this research, layer thickness of 0.007”, 0.01” and 0.014” have been considered. The following figure illustrates the effect of various layer thickness on the stair-stepping effect.

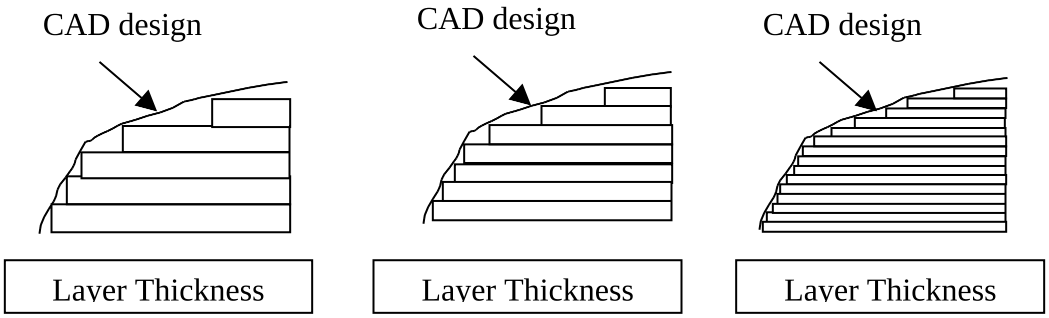

Figure 2 Effect of Layer Thickness on Stair-Stepping

The surface inclination determines the exposure of the sub-perimeter regions in a layer. At lower inclinations the roughness is also due to the sub-perimeter region that is exposed. The sub-perimeter [6] region is composed of individual roads separated by the air gap. The air gap is set at zero in the QuickSlice® software, however when the part is built there is always a physical gap between adjacent roads as shown in figure 5. Hence, the road width, the air gap and the fill pattern determine the surface roughness values at low inclinations. In this work, the road width and the air gap are varied and their effect on the surface roughness is determined.

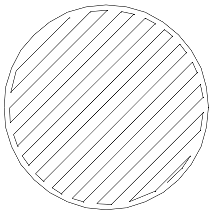

Figure 3 Sub-perimeter voids

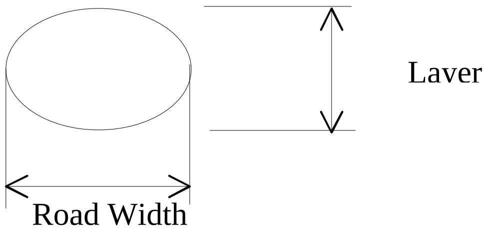

Figure 4 Road Width and Layer thickness

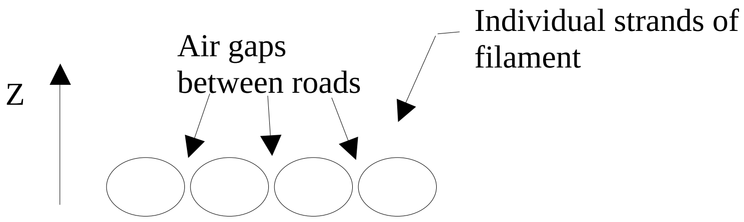

Figure 5 Cross-section of a layer showing roads and the air gap between roads

Model temperature is the liquefier chamber temperature. This is the temperature at which the model material is melted. The variation in model temperature would affect the fluidity of the material as it is being laid. This factor was selected to see if it influences the surface roughness. The levels considered were 250^{o} C, 270^{o} C and 280^{o} C. At higher temperatures it was expected that the material would be in a more fluid state, thus it would lead to more bulging of the material as it is being laid down. This would result in rounding off of the stair-steps thus leading to better surface finish. Figure 6 illustrates the effect.

At higher temperatures, rounding is more pronounced

At low temperatures, rounding is less pronounced

Figure 6 Illustrates the effect of Model Temperature on the shape of the deposition

The table given below lists the process parameters considered and their settings.

FACTORS	**LOW LEVEL**	**CENTER POINT**	**HIGH LEVEL**
Layer Thickness (A)	0.007 Inches	0.01 Inches	0.014 Inches
Road Width (B)	0.0120 Inches	0.0170 Inches	0.0220 Inches
Air Gap (C)	-0.0005 Inches	-0.000075 Inches	-0.001 Inches
Build Orientation (D)	20 Degrees	45 Degrees	70 Degrees
Model Temperature (E)	250^{o} C	270^{o} C	290^{o} C

Table 1 Parameters and their levels

Now that the factors have been identified and their levels established, an experiment should be suitably designed. A fractional factorial experiment with five center points is conducted. With five factors and two levels for each factor, a full factorial design would come to 32 runs. In order to understand the main effects with less number of runs, a half-factorial design was used. This resulted in the compromise of higher order interactions because of the aliasing nature of the fractional designs. Center Points are considered in order to get an estimate of the error in the experiment and for the non-linearity of the result. A half-factorial design with five center points resulted in 21 runs.

Before the actual experimentation, each run was reviewed to make sure that the parts were physically possible to build. The runs were randomized in order to eliminate any bias due to time or unintended ordering of the runs.

Procedure

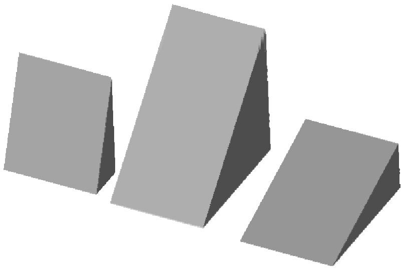

Figure 7 Up-facing angles 70^o, 45^o and 20^o

Once the approach was established, a series of 3 parts with up-facing angles of 20^o, 45^o and 70^o were designed in AutoCAD©. The parts are shown in Figure 6. The parameters Layer Thickness, Road Width, Air Gap were set in the QuickSlice™ software. The Model Temperature was varied with each build on the Control Panel of the FDM 1650. For a factorial design of 2^{5-1} with five center points, a total of 21 parts were built with different settings of the parameters. The roughness values on the 21 surfaces were obtained by using a Sheffield Profile Measurement System, a contact type surface measurement system. Two measurements were taken per surface and an average of this was taken for analysis. Each measurement was taken over a length of ten times the cut-off length of 0.030". Hence, the roughness of a surface is actually an average of values taken over ten cut-off lengths. R_a, the roughness is defined as the arithmetic mean of absolute values of profile departures from the centerline within the evaluation length. The measurements are taken at an angle of 45^0 to the lay direction. According to the ASME B46.1 – 1995 standard for Surface Texture, roughness measurement should be taken perpendicular to the lay direction. This becomes cumbersome because the hatch patterns in adjacent layers are perpendicular to each other as can be seen from the following figure.

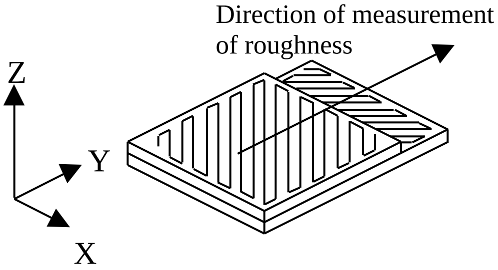

Figure 8 Cross-hatching across adjacent layers

Analysis

For the analysis of the 21-run fractional factorial design, the Surface Roughness response variables were analyzed using the Design-Expert® software.

The procedure for the analysis of the surface roughness response variable was performed as follows:

1. The response variable was chosen.
2. The effects were calculated.
3. Significant effects were chosen from the graph.
4. Statistical model was fit to the data.
5. Model Diagnostic analysis was performed.
6. The Model Graphs were analyzed.

A typical output of the analysis is given in Table 2. The main effects and their interaction are calculated. Next the normal probability plot is used to select the significant effects. Figure 9 shows the half-normal probability plot of the effects. From this plot, it is evident that the factors layer thickness and part orientation and their interaction have a significant influence on the response. Rest of the effects are just error terms and they fall on the straight line. From the ANOVA model a predictive equation for the response can be constructed from the calculated coefficients. In this case the final model in terms of coded variables is given below

Roughness = +1020.76 + 157.51 * A - 207.66 * D + 138.25 * A * D

A and D have common values of +1,0 and –1. This equation can be used to predict the surface roughness values.

	Term	Effect	% Contribtn
Model	**A**	**315.012**	**23.8828**
Error	B	15.6375	0.0588524
Error	C	-5.35	0.0068887
Model	**D**	**-415.325**	**41.5151**
Error	E	-98.8875	2.35349
Error	AB	-63.8125	0.980035
Error	AC	4.825	0.00560305
Model	**AD**	**276.5**	**18.4001**
Model	**Curvature**	**138.63**	**4.62536**

Table 2 Estimate of Effects

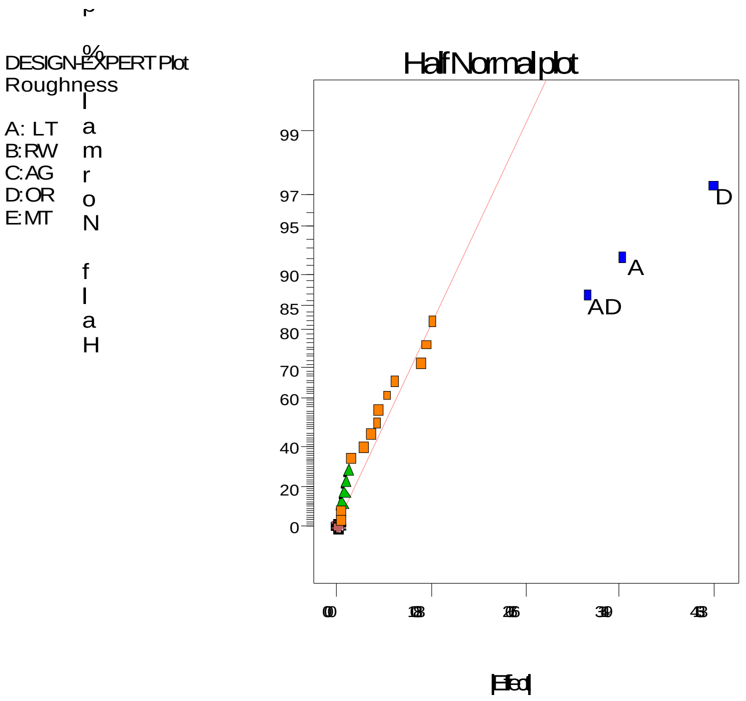

Figure 9 Half Normal Probability Plot

The residual analysis and model adequacy checking are done to determine the validity of the model and to check if any outlier points unduly influence the results.

Increase in layer thickness results in a significant increase in the stair-stepping effect. Thus the surface roughness showed an increase with increase in layer thickness. The plot shows the effect of layer thickness on surface roughness.

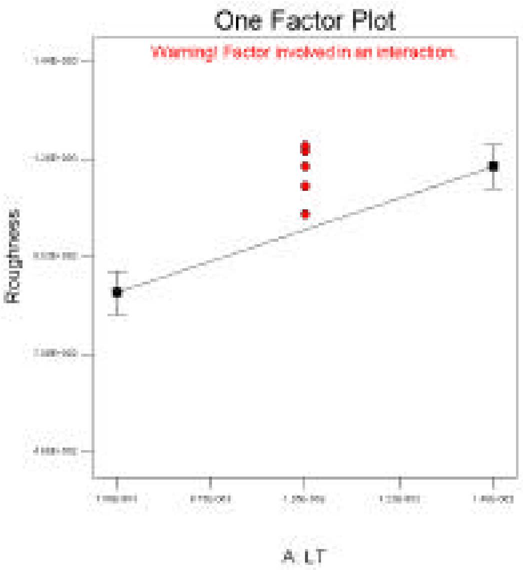

Figure 10 Plot of Surface Roughness Vs. Layer Thickness

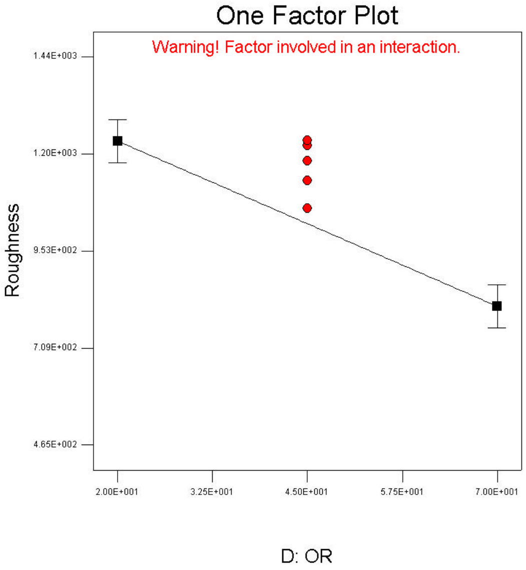

Figure 11 Plot of Surface Roughness Vs. Part Orientation

Orientation affects the stacking of layers on top of each other. At lower angles the adjacent layers are offset by a greater distance, thus resulting in coarser surfaces.

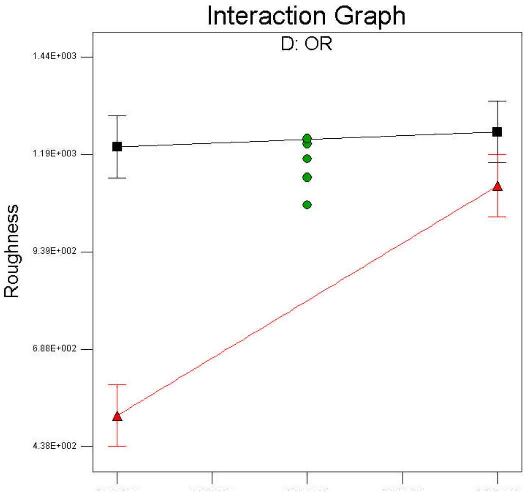

Figure 12 Interaction Plot of Surface Roughness Vs. Layer Thickness and Part Orientation

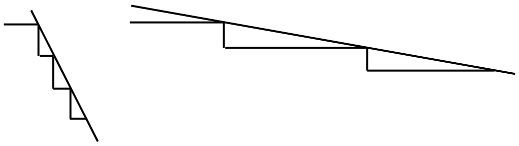

Figure 13 Offset between layers affect surface roughness on a steep and shallow inclinations

It can be inferred from the interaction plot that the roughness values are at a minimum for a low setting of layer thickness and a high setting of part orientation.

Conclusion

Layer Thickness and Part Orientation proved to be the significant factors in determining the surface quality of the part. A layer thickness of 0.007” and part orientation of 70^o resulted in the best surface finish. Model Temperature, Air Gap and Road Width did not have much influence on the surface finish of the part. Adding more parameters including material properties and other process parameters like hatch patterns, envelope temperature would result in an accurate and useful model to predict surface finish. A model with increased number of levels and a random effects model can be used to provide more insight on the sensitivity of surface finish to process parameter variation. Future advances in surface finish could include better post-processing techniques and improvements in the FDM hardware and the control system. Using the half-factorial design resulted in cutting down the number of runs made for finding the best parameters.

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References

[1] Diane A. Schaub, Kou-Rey Chu, Douglas C. Montgomery, “Optimizing Stereolithography Throughput”, Journal of Manufacturing Systems, Vol. 16/No.4, 1997

[2] Diane A. Schaub, Douglas C. Montgomery, “Using Experimental Design to Optimize The Stereolithography Process”, Quality Engineering, 9(4), 575-585 1997

[3] A. Armillotta, G.F. Biggioggero, M. Carnevale, M. Monno, “Optimization Of Rapid Prototypes With Surface Finish Constraints: A Study On The FDM Technique”, Proceedings 3rd International Conference on Management of Innovative Technologies, Piran, Slovenija, 28-29 October 1999

[4] Gautham Kattethota, Mark Henderson “A Visual Tool to Improve Layered Manufacturing Part Quality”, Proceedings of the Solid Freeform Fabrication Symposium, Austin, TX, August 10-12, 1998, pp. 327-334

[5] Reeves, P.E. Cobb, R.C., “Surface Deviation Modeling of the LMT Process – A Comparative Analysis”, 5th European Conference on Rapid Prototyping and Manufacturing, pp. 59 – 75

[6] Jamalabad, V.R. et al., “Process Improvements in Fused Deposition of Ceramics (FDC): Progress towards structurally sound components”, Proceedings of the 1996 ASME Design for Manufacture Conference, Irvine, CA, August 1996, pp. 18-22

[7] James W. Comb, William R. Priedeman, Patrick W. Turley, “FDM Technology Process Improvements”, Proceedings of the Solid Freeform Fabrication Symposium, Austin, TX, 1994

[8] Douglas C. Montgomery, Design and Analysis of Experiments, 3rd edition (New York: John Wiley & Sons, 1991)