Optimizing the Surface Roughness of Additive Manufacturing Samples Using Design of Experiments (DOE)

Rafiq Noorani, Tristan Minter, Charles Hill, Alex Minor, Devansh Patel, Xiaodong Sun

Abstract—Additive manufacturing technology is used in industry that works by systematically depositing layers of working material to construct larger, computer- modeled parts. A key challenge associated with this technology is that additive manufacturing parts often feature undesirable levels of surface roughness for certain applications. To combat this phenomenon, an experimental technique called Design of Experiments (DOE) can be employed during the growth procedure to statistically analyze which 3D printed growth parameters are most influential to part surface roughness. Utilizing DOE to identify such factors is important because it is a technique that can be used to optimize a manufacturing process, which saves time, money, and increases product quality. In this study, statistically designed experiments have been used to determine the processing factors that affected the surface roughness of rapidly prototyped ABS polymer on 3D printing. 3D Printing (3DP) is a special class of additive manufacturing systems whose prices are generally less than $5K. A two-level, three-factor full factorial experiment was used to select the best combination of factor levels that minimized the surface roughness of Raise3D E2 modeled test specimens. The chosen factors were model temperature, layer height, raster orientation. Some of the factors and their two-factor interactions were shown to significantly affect the surface roughness. All of the factors and their two and three factor interactions are studied to investigate their effects on the surface roughness of the polymer materials. These results are explained using statistical analysis and physical interpretation.

R. Noorani is a professor at Loyola Marymount University, Los Angeles, CA 90045,USA. (phone: 310-338-2831; fax: 310-338-6029; e-mailrnoorani@lmu.edu).

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I. Introduction

THE objective of this project is to demonstrate the effectiveness of Design of Experiments (DOE) technique to minimize the surface roughness of additive manufacturing samples using a Raise3D E2 printer[1]. 3DP is extremely advantageous in the manufacturing industry because of its speed and simplicity. 3D printers are part of additive manufacturing that cost less than $5K. Instead of taking weeks or months to create a part, this technology can create a prototype within several hours [2]. As a result, this technique has been utilized more and more in industry because of its ability to reduce errors, time, and cost in aspects of the manufacturing process. However, 3DP does not come without its flaws. One problem with 3DP parts is that they can feature undesirable levels of surface roughness. This roughness can lead to increased friction, heat generation, and energy loss during application of these parts. This decreases the product's life while also increasing costs. Therefore, it is highly desired both in academia and industry to determine new ways to consistently minimize the surface roughness of 3DP samples [3].

DOE is a technique used to statistically design and analyze experiments in which many parameters influence an output response. To do this, DOE works by statistically varying all of the factor combinations and then analyzing the response to determine the effects of the factors. DOE is highly beneficial in the manufacturing industry because it can lead to improved accuracy and consistency of

Tristan Minter, Charles Hill, Alex Minor, and Devansh Patel are undergraduate students of Mechanical Engineering at Loyola Marymount University, Los Angeles, CA 90045, USA.

the output response (in this case surface roughness), which leads to greater efficiency and lower cost. Pioneered first in the 1930s by Sir Ronald Fisher in England and then developed further by Japanese statistician Genichi Taguchi in the 1950s and 60s, DOE is now widely used throughout the automotive and aerospace industries to optimize production [4].

This research is performed as a two-level/three factor DOE experiment [5]. These factors/parameters are model temperature, layer height, layer orientation. For each of these factors, a high level and a low level are chosen. All eight possible growth combinations are performed, and their surface roughness values (Ra) are measured. With this done, the samples are analyzed using statistics to determine the level at which each factor should be maintained to consistently minimize the surface roughness [5].

Through performing this DOE technique, it is expected to experimentally determine which parameter (temperature, layer height and layer orientation) is most significantly affecting the surface roughness of the parts, while also determining the optimized factor levels to minimize surface roughness [6].

II. Theory

Rectangular 3DP samples were studied in this research and were constructed using a Raise 3D E2 printer. These samples were prototyped with three variable growth parameters on the Raise 3D E2 system. The parameters that were varied were the model temperature of the part, the layer height at which the machine deposited the working material (PLA plastic), the layer orientation to grow the part. For each of these three parameters, both a high and low level was selected. These parameters and the experimental arrangement are illustrated below in Table 1 and 2. In Table 2, N is used to designate the run number, "-1" is used to designate the low level of the factor, and "+1" is used to designate the high level.

TABLE 1
FACTORS AND LEVELS

	Factors	**Low**	**High**
A	Temperature (Celsius)	195	220
B	Layer Height (mm)	0.1	0.3
C	Orientation (Degrees)	0	90

TABLE 2
EIGHT EXPERIMENTS

ID		**Factors**			**Slicer Settings**		
Sequential	Random	A	B	C	Temp(C°)	Layer Height	Orientation
1	1	1	1	1	195	0.1	0
2	5	1	1	2	195	0.1	90
3	4	1	2	1	195	0.3	0
4	3	1	2	2	195	0.3	90
5	8	2	1	1	220	0.1	0
6	7	2	1	2	220	0.1	90
7	6	2	2	1	220	0.3	0
8	2	2	2	2	220	0.3	90

With two levels and three factors, eight different growth combinations could be performed ($2^3 = 8$ different combinations). For each of these 8 growth conditions, 5 replications were made, leading to a total of 40 samples. After growth, these samples were measured using a surface profile measurement device that outputs their surface roughness, Ra, in micrometers. With all of these data points, DOE was employed to statistically analyze the influence of each factor on the resulting surface roughness. The aim of this DOE analysis is to determine a regression equation (Equation 1 below), which is used to verify and predict the experimental surface roughness values as a function of the differing growth parameters [7]. With this system equation, the effect of these factors can easily be seen in order to minimize the surface roughness.

III. Procedure

The general procedure of this experiment was as follows:

- Using the Raise 3D 2E machine, 5 samples were grown corresponding to each of the 8 growth parameter combinations shown in Table 2.
- Using a surface profile measurement system, the surface roughness (Ra) values of the samples were obtained.
- Using DOE analysis, the system equation for surface roughness as a function of growth factors was found
- From the DOE data and values of surface roughness, the response was plotted using a DOE mean plot to determine the most

important factors and the interaction effects of factors.

IV. RESULTS & DISCUSSIONS

The results of the research are shown below. Table 3 shows the results obtained for the surface roughness for each batch of five replications for each of the 8 trials. The Y average is the total average of all the Y responses from each trial measured. The average results are also verified by using a system equation, as shown in Equation 1, whose function is to minimize the surface roughness, Y_{min}

$$Y\,min = \overline{Y} + c_A A + c_B B + c_C C + c_D D + c_{AB}(AB) + c_{AC}(AC)$$
$$+ c_{AD}(AD) + c_{BC}(BC) + c_{BD}(BD) + c_{CD}(CD) + c_{ABC}(ABC)$$
$$+ .. + Error \ldots\ldots (1)$$

TABLE 3
MEAN AND Y SYSTEM

	Y_{mean}	Y_{system}
I	(microns)	(microns)
1	21.2	20.895
5	2.88	3.185
4	18.8	19.105
3	0.84	0.535
8	14.76	15.065
7	1.6	1.295
6	16.16	15.855
2	0.92	1.225

Where Y is the grand average and c values are the coefficients. The results show that there is a statistically superior set of parameters that will minimize the surface roughness. Looking at the results, samples 3, 2, 7 and 5 produced the best results, of which samples 3 and 2 produced the best of all. While the results are not conclusive, the temperature, layer height and the orientation all contributed to the lower surface roughness.

The physical interpretations of the A, B and C factors are explained below.

A - Model Temperature. Since polymers are thermal insulators, the higher temperature allowed more time for viscous flow of the deposited liquid layer into the large pores, which would reduce the size of the strength-limiting pores. Hence, having the highest ultimate strength with most of the factors high level is logical.

B - Layer Height. The higher layer thickness is expected to have a greater fiber volume fraction, which would translate into improved strength.

C - Raster Orientation. The 0°/90° orientation has one strand in complete tension while the other is in complete shear.

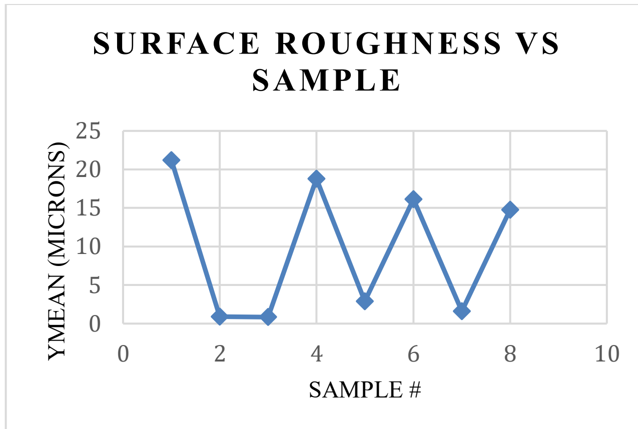

Figure 1: Surface Roughness vs Samples

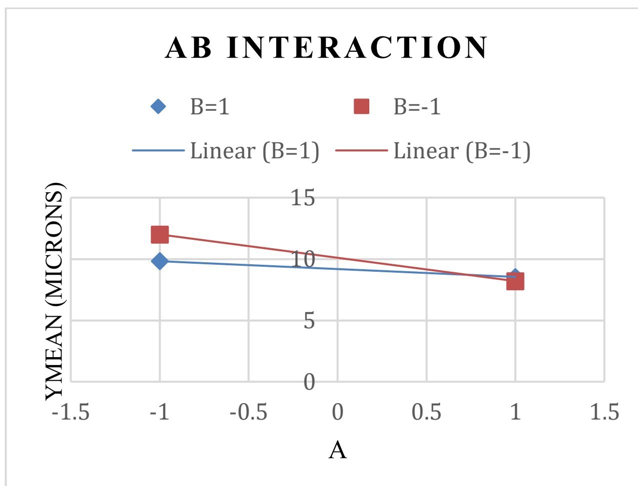

Figure 2: AB Interaction

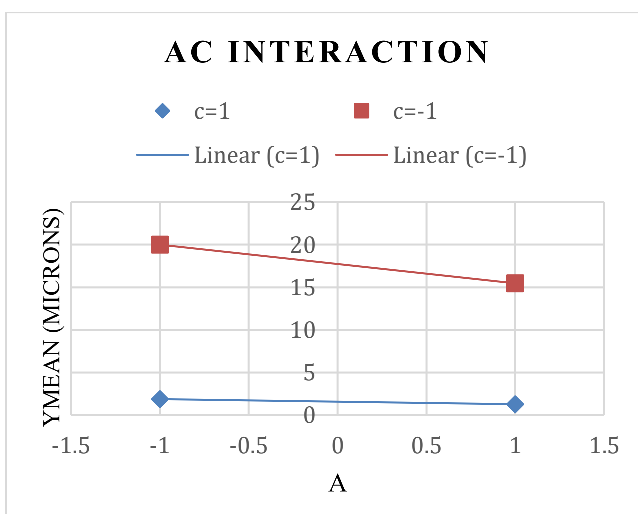

Figure 3: AC Interaction

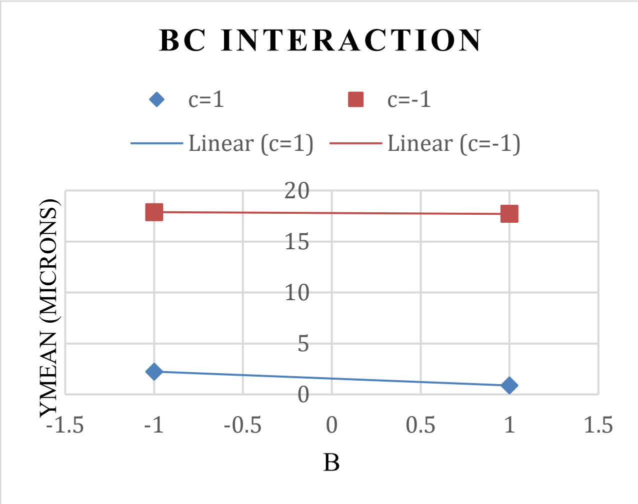

Figure 4: BC Interaction

V. Conclusions

After completing this experimental study, the following conclusions can be made:

- The hypothesis that DOE technique can effectively be used to minimize the surface roughness of RP prototypes is accepted
- The minimum surface roughness occurred when the factors were set at low temperature, high layer height and 0 orientation.
- There is a strong resemblance between the results of the Ymean and Ysystem, reinforcing the accuracy of Ymean. It validates the results of the experiment.
- From the interaction graphs, it is clear that the factors A and B interact, meaning A depend on B and vice versa while the factors A & C and B & C do not interact significantly.
- This experiment should be repeated many times in order to more fully determine the statistical significance of deposition temperature, layer height, and orientation on surface roughness
- This experiment should be improved through repetition to identify and eliminate human errors.

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