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IMPROVEMENT OF SURFACE ROUGHNESS ON ABS 400 POLYMER MATERIALS USING DESIGN OF EXPERIMENTS (DOE)

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Abstract

The objective of this research was to find the best combination of factor levels that minimized the surface roughness of prototyped samples from Fused Deposition Modeling (FDM). Two sets of experiments were conducted for that purpose; a two-level three-factor full factorial experiment and a three-level two-factor full factorial experiment. The parameters chosen for this research were *model temperature*, *layer thickness* and *part fill style*. The results obtained from both experiments were compared and analyzed in order to determine the best combination of factors that minimized the surface roughness of the specimens. The significant factors, their interactions and the optimum setting are presented in this paper

Introduction

Rapid Prototyping (RP) is a process that is used for fabricating solid prototypes from a computer-aided design (CAD) data file [1]. RP is finding its applications in diverse fields of industry today, with prototypes used for form, fit and function, design verification, early detection of error and reduction of waste [2-3]. Design engineers around the world use RP to pre-estimate product characteristics such as shape, manufacturability and surface 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. Common surface defects include the staircase effects, support structure burns and errors due to starting and ending of deposition [4].
FDM is a complex technology that involves many different process parameters. An experimental design technique is a useful tool to improve the surface finish on a part by analyzing the effects of the processing factors. Surface finish is a function of a number of factors. Some of these factors are model temperature, layer thickness, part fill style, and visible surface. An optimal setting of these parameters involved in the build process would result in a FDM prototype with good surface quality [5]. The purpose of this paper is to use the quality engineering tools to design, analyze and physically interpret our selection of the FDM processing factors and their levels.

Design of Experiments

The experimental system used consists of a FDM-1650 machine and Surtronic Plus surface roughness measuring instrument. A cause-effect diagram was used to list the possible causes affecting the surface roughness of the test specimens. Three factors were selected for the two-level three-factor full factorial experiment: (A) model temperature, (B) layer thickness, and (C) visible surface. On the other hand, the three-level two-factor full factorial experiment was made with only two factors due to a lack of a factor with a third level. The factors chosen were (A) model temperature, (B) layer thickness. Factors for the first experiment have two levels, i.e., low (-1) and high (1), respectively, which are shown in Table 1.

Parameter (Factor)	Description	Low Level (-1)	High Level (1)
A	Model Temperature (C)	270	274
B	Layer Thickness (in)	0.007	0.01
C	Visible Surface	Normal Rasters	Fine Rasters

TABLE 1 FACTORS AND LEVELS

Parameter (Factor)	Description	Low Level (-1)	Medium level (0)	High Level (1)
A	Model Temperature (C)	270	272	274
B	Layer Thickness (in)	0.007	0.0085	0.01

TABLE 2 FACTORS AND LEVELS

The second experiment have three levels, i.e., low (-1), medium (0) and high (1)**.** First, a two-level three-factor full factorial experiment was conducted and sixteen experimental trials were selected and randomized. In order to reduce the effects of unknown systematic variation such as ambient temperature, the runs were randomly reordered in a new table. The same procedure was followed for the three-level two-factor full factorial experiment with the difference that 9 trials were selected and randomized [5].

Two-level Three-factor Full Factorial Experiment Data Analysis

Based on the results in Table 3, the column effects containing the three way interaction can be ignored in the analysis due to their low effect on the results. By comparing the Delta/2 values, we can state that when the Delta/2 values of the parameters and interactions are significantly lower than the greater of them, the effect is not significant; therefore, those parameters can be eliminated. However, if one interaction has a low value but contains one of the single parameters which has a high value, this interaction can not be eliminated. Interactions may also be checked by plotting them as two lines. If these lines cross each other, it means that the interaction is strong whereas if the lines are parallel to each other, it represents a weak interaction and has little effect on the results.

N	I	Factors			COMBINATIONS				Measurements			Residuals			Y mean	S
		A	B	C	AB	AC	BC	ABC	Ra	Rb	Rc	R1	R2	R3		
5	1	-1	-1	1	1	-1	-1	1	5.55	5.37	6.57	-0.28	-0.46	0.74	5.83	0.64714759
8	1	1	1	1	1	1	1	1	5.7	7.5	5.7	-0.60	1.20	-0.60	6.30	1.03923048
1	1	-1	-1	-1	1	1	1	-1	14.5	15.8	20.4	-2.40	-1.10	3.50	16.90	3.1
4	1	1	1	-1	1	-1	-1	-1	23.9	27.1	31	-3.43	-0.23	3.67	27.33	3.55574652
3	1	-1	1	-1	-1	1	-1	1	33.5	33.4	31.6	0.67	0.57	-1.23	32.83	1.06926766
6	1	1	-1	1	-1	1	-1	-1	6.9	4.9	12.2	-1.10	-3.10	4.20	8.00	3.77226722
2	1	1	-1	-1	-1	-1	1	1	17.5	29.7	10.8	-1.83	10.37	-8.53	19.33	9.58244923
7	1	-1	1	1	-1	-1	1	-1	7.6	5.6	7.2	0.80	-1.20	0.40	6.80	1.05830052
Delta	16.65	-0.17	2.90	-8.68	-1.33	0.59	-3.08	0.66								
Delta/2		-0.09	1.45	-4.34	-0.66	0.30	-1.54	0.33								

System Equation

Y = 16.65 - 0.09***A** + 1.45***B** - 4.34***C** - 0.66***AB** + 0.30***AC** - 1.54***BC** + 0.33***ABC** + ERROR

A = Model Temperature **C = Visible Surface**
B = Layer Thickness

Run	Y
N = 5	5.83
N = 8	6.3
N = 1	16.9
N = 4	27.3333
N = 3	32.8333
N = 6	8
N = 2	19.3333
N = 7	6.8

Lower Surface Roughness
1st 2nd 3th 4th

Combination influence
Strong Weak

Lower Variability
1st 2nd 3th

Factor influence
1st 2nd 3th

TABLE 3
THREE-FACTORS TWO LEVELS FULL FACTORIAL ANALYSIS TABLE

From the analysis table (Table 3), the main factors C, and B, as well as the interaction factor BC, were determined to be the most important factors that could minimize the surface roughness. Three grade interactions are neglected for having little contribution to the results. A *system equation* was used to find which set of factor settings gives the lowest Y (surface roughness). Then, the values of Y were calculated and displayed in Table 3 to be compared to each other.

The system equation has the mathematical form of the selected model and is only as good as the model. The coefficients in the equation are empirically derived for the given model, using simple regression that were performed in Table 3 [6]. The values of the coefficients c_A, c_B, c_C, c_{AB} and so on are obtained from each Delta/2 in Table 3 whereas the grand mean, $\bar{y}$, was obtained from the value of Delta when all factors are high (1)**.** The system equation is given as follows [7]:

$Y = \bar{y} + c_A A + c_B B + c_C C + c_{AB} AB + c_{AC} AC + c_{BC} BC + c_{ABC} ABC + ERROR$

The error term is never known. It exists due to a combination of the model fit limitations, measurements errors, the presence of unknown nuisance factors (such as air temperature and humidity, the worker state of mind at a given time, etc.), and perhaps, the fact that certain active factors have been ignored in the model. The complete equation with the coefficients is displayed at Table 3.

Three-level Two-factor Full Factorial Experiment Data Analysis

The nine experimental trials were conducted by testing the combination of factor levels from Table 2 in the experimental design matrix for each trial. The mean *surface roughness* is calculated for each trial and is recorded in the proper factor level cell of the response table (Table 4). At the bottom of the table, the total, mean and effect are shown. The mean effect is the largest difference between the levels of each factor.

	Model Temperature (A)			Layer Thickness (B)			No Factor			No Factor			
RUN	**-1**	**0**	**1**	**-1**	**0**	**1**	**-1**	**0**	**1**	**-1**	**0**	**1**	**Yi (μm)**
1	17.83			17.83			17.83			17.83			**17.83**
2	22.57				22.57			22.57			22.57		**22.57**
3	32.10					32.10			32.10			32.10	**32.10**
4		26.03		26.03				26.03				26.03	**26.03**
5		27.27			27.27				27.27	27.27			**27.27**
6		28.67				28.67	28.67				28.67		**28.67**
7			12.30	12.30					12.30		12.30		**12.30**
8			24.90		24.90		24.90					24.90	**24.90**
9			32.67			32.67		32.67		32.67			**32.67**
Total	**72.50**	**81.97**	**69.87**	**56.17**	**74.73**	**93.43**	**71.40**	**81.27**	**71.67**	**77.8**	**63.54**	**83.03**	
Mean	**24.17**	**27.32**	**23.29**	**18.72**	**24.91**	**31.14**	**23.80**	**27.09**	**23.89**	**25.92**	**21.18**	**27.67**	
Effect	**4.03**			**12.42**			**3.30**			**6.50**			

TABLE 4
RESPONSE TABLE

We can clearly see by looking at the mean effect in Table 4 that the layer thickness has more influence over the surface roughness than the temperature. All interactions are plotted against surface roughness in order to see the effects between them (Fig. 1). If the lines created on the plot are not parallel, it means the interaction is strong. If the lines are parallel to each other, it is a weak interaction and has little effect on the results.

From Table 4 the unassigned factor columns show greater mean effects than the model temperature (A). This indicates their random variation is greater than the mean effect of temperature (A). Therefore, the variation in temperature is statistically insignificant because its mean effect (Figure 1 and Table 4) is less than experimental error.

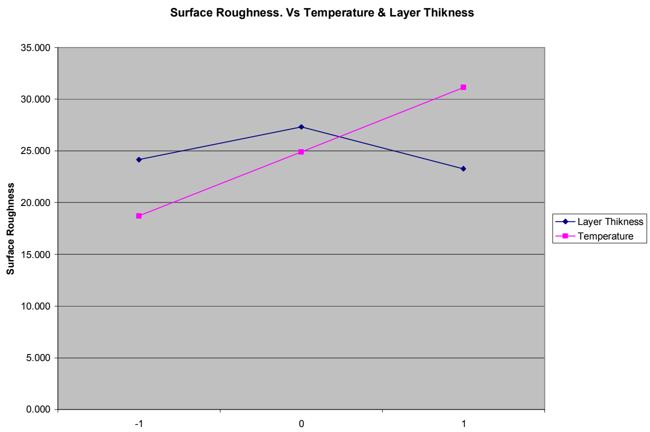

FIGURE 1
SURFACE ROUGHNESS vs. TEMPERATURE & LAYER THIKNESS

Conclusions

Using the statistically designed experiments, the following conclusions are reached:

For three factor, two level experiments, minimum surface roughness (5.83 µm) occurs when: A = -1 (270 C *temperature*), B = -1 (0.007 in *layer tthickness*) C = 1 (*fine rasters*). Layer thickness has more effect over the *surface roughness* than the *temperature*. All three factors have a significant effect on the surface roughness, and they interact with each other.

For two factor, three-level experiment, minimum surface roughness (12.3 µm) occurs when: A = 1 (274 C temperature), B = -1 (0.007 in layer thickness).

Upon further analysis, it is concluded that the layer thickness has greatest effect on the surface roughness. The lowest layer thickness gives the lowest roughness. Effect of model temperature on roughness is statistically insignificant. However, the highest model temperature is recommended because this would smooth out surface and provide a lower layer thickness.

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