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Design for AM: Contributions from surface finish, part geometry and part positioning

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Abstract

With the increase in production final parts by Additive Manufacturing, the study of the surface finish and dimensional accuracy become critical, in order to determine if it is possible to avoid costly and time-consuming post-production, especially when using Fused deposition Modelling of Polymers. This is especially true when the goal is functional parts, where the surface quality and dimensional accuracy may preclude the use of FDM. With that in mind a study was performed to evaluate the surface finish and dimensional deviations of FDM parts, when considering multiple processing parameters, by way of a design of experiments coupled with response surface methodology. The results showed that the critical parameters were face orientation, layer height and printing speed, and equations predicting the surface finish and dimensional accuracy were obtained, with further experimental results validating the equations. With these equations we propose guidelines for manufacturing part by FDM when surface finish and/or dimensional accuracy is of importance, so that a designer knows what changes can be made to a part and what precautions must be taken when printing said part, in order to comply with a specified surface finish/dimensional tolerance.

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1. Introduction

Under the umbrella term of Additive Manufacturing (AM), there are 7 families of technologies that are used for turning virtual 3d models to physical parts [1].

Although it started as a rapid prototyping technology, used in conceptual design and manufacturing checks among others [2], AM, with its increase in quality and decrease in cost, quickly disseminated throughout various industry clusters [3].

AM is now a technology used for production of small batches, or one of a kind parts, producing end use parts for multiple products [4]–[7].

One of such technologies is Fused Deposition Modelling (FDM), widely used in the prosumer market due to its low acquisition cost, as well as in companies with low production volume and/or high complexity parts. FDM is part of the material extrusion family, in which a continuous filament of thermoplastic material is fed into a printhead, where heat is

applied so that the semi molten filament can then be extruded to form a part layer by layer [8].

The manufacturing of end use parts introduces several new constraints to the production by AM technologies. These constraints are:

- Surface roughness - A typical end use part has to adhere to a maximum value(s) of roughness, measured in (μm). There are several way of measuring surface roughness, with the most commonly used being Ra which is the arithmetic mean deviation.
- Dimensional Tolerances – Maximum deviation allowed for a given element.
- Geometrical Tolerances – Maximum deviation allowed for a given feature geometry, often in relation with other features.

Although post processing is used in most cases, and several techniques have been studied [9]–[11] the study of the roughness and dimensional tolerances of net shape parts is of interest for applications where such constraints are more relaxed, *i.e.*, when the requirements are less stringent. Furthermore, given that the technology has seen a rapid evolution new studies are required.

As such this work focuses on determining the surface roughness, using Ra, and dimensional tolerances, (outputs), of an FDM machine using PLA as feedstock, and the manufacturing parameters (inputs) that influence both tolerances. This is accomplished by performing a design of experiments (DoE) to determine the influential parameters, coupled with the response surface methodology (RSM), to obtain predicting equations that correlate the influential parameters with the outputs.

A DoE is a technique used to analyse several system inputs and the response of the output(s) to the variations in inputs [12]. By testing multiple possible inputs at once, it avoids one factor at a time (OFAT) techniques, that are costly, time consuming, and as important, cannot test for interactions between inputs, which might be of relevance to a particular system [13]. RSM is a statistical technique used to obtain the relationship between the system inputs and outputs, for a given range of input parameters, in order to understand the system or in optimization studies, improving the system response (outputs) by optimizing the inputs. Developed by Box and Wilson [14], it uses a second-degree polynomial to model the system response, that although an approximation, it is of great help to understanding complex systems or when there is little information. It has seen use in the AM field, with Taufik [11], using RSM to model the roughness of an ABS part finished by laser; Mohamed [15], used RSM to study the influence of several parameters on build cost and dimensional errors; Mohamed [16], used RSM to optimize FDM parameters to increase flexural modulus; and Rathee [17] used FDM to study build time requirements.

2. Materials and methods

2.1. Printer, Material and Specimen

The printer used was a Blockstec Blocks One (Figure 1), a CoreXY FDM printer with the specifications shown in Table 1.

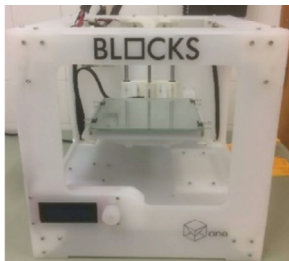


Figure 1 – Blockstec Blocks One

Table 1 – Blockstec Blocks one properties

Printing Properties	Blocks One
Technology	FDM
Extruder	0.4 mm @ 180-260 °C
Print Volume	200x200x200 mm
Layer Thickness	50 to 300 microns
Print speed	Up to 100 mm/s
Material	1,75 mm PLA

The material used was Filkemp's Poly Lactic Acid (PLA) PLA-N.

The specimen shape for the roughness tests were that of a cube with 10 mm per side, which allowed for the measurement of 3 faces per test (figure 2).

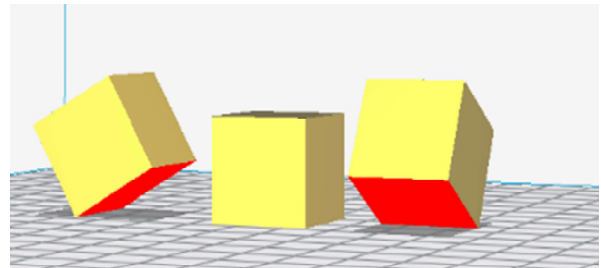


Figure 2 - Specimens used in tests

For the dimensional deviation tests a 3-axis test specimen was created. In this case since the goal was to measure dimensional accuracy among the axis no rotation was performed (Figure 3).

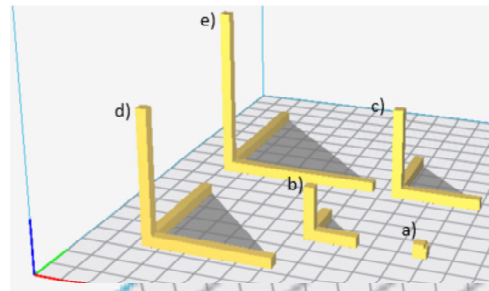


Figure 3 – test specimens used in the measurements of dimensional deviations. a) 5mm b) 20mm c)35mm d) 50mm e) 65mm.

2.2. Experimental procedure

The experimental procedure was as follows

- Identification of the likely important parameters
- Create a full factorial DoE.
- Measure the surface roughness/dimensional variation from the nominal value
- Perform ANOVA to determine the important Perform a RSM using the Central Composite Design (CCD) to ensure rotatability, in order to obtain the response equation.

3. Results and Discussion

3.1. Screening experiments

The input variables considered to be of influence on the surface finish and dimensional deviations are:

- Infill Percentage ($I\%$)
- Layer Thickness (Lt)
- Print Speed (v)
- Extrusion temperature (T)
- Size (Sz) (Dimensional Only)
- Orientation (Θ) relative to the print bed (roughness only)

With these parameters both DoE require 2^5 specimens with 5 specimens for each variable combination, resulting in a full factorial DoE. With the DoE complete an Analysis of Variance (ANOVA) was performed to determine the variables that have the most impact on the responses (Table 2).

Table 2 – Important variables after screening

Influencing variables	Responses	
	Roughness	Dimensional
	Lt	Lt
Θ	v	
v	T	
	Sz	

With the most important variables determined, the RSM using a CCD was performed to obtain the equations predicting the response behavior to changes in variables. The relation between RSM Levels and the values of the variables are shown in tables 3 and 4.

Table 3 – RSM levels and relation to variables (roughness tests)

Input	Level				
	-1.682	-1	0	1	1.682
Lt [mm]	0.05	0.7	0.1	0.13	0.15
v [mm/s]	8	25	50	75	92
Θ [°]	-5	15	45	75	95

Table 4 - RSM levels and relation to variables (dimensional variation tests)

Input	Level				
	-2	-1	0	1	2
Sz [mm]	5	20	35	50	65
Lt [mm]	0.05	0.1	0.15	0.2	0.25
v [mm/s]	10	30	50	70	90
T [°C]	200	205	210	215	220

The tables with the results of the RSM are shown in the appendix.

3.2. RSM Roughness

The roughness results of the RSM are shown in Equation 1
 $Roughness = 12.417 + 3.956Lt - 4.404\theta - 2.219 Lt\theta$ (1)
 With an Adjusted R^2 of 77.25%.

Equation 1 shows that the surface roughness decreases as Lt decreases and θ increases. The reason for the first one is that with lower Layer thickness the smaller the difference between peaks and valleys. Orientation wise, for very small angles in the XoY plane the staircase effect of the layer by layer deposition of AM is very pronounced which increases surface roughness.

The adjusted R^2 is quite good, although there is a caveat. In AM there are two orientations where the values of roughness are significantly smaller than for any given direction, specifically 0° and 90° . At these orientations, the deposition has no staircase effect which significantly decreases roughness. Figure 4 shows this difference in roughness.

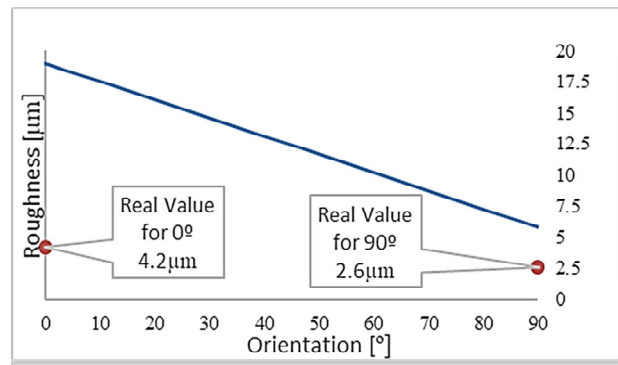


Figure 4 – Roughness along Θ with Lt at Level 0 (0.1 mm)

As the figure shows the roughness is ever decreasing from 0° to 90° , but the real values at those points are smaller. Since these points do not appear in any level of the RSM, this discontinuity in surface roughness does not appear in the equation, and as such the equation is not valid at 0° and 90° .

3.3. RSM dimensional deviation

The dimensional deviations results of the RSM are shown in Equation 2, 3 and 4.

$$Dim_x = -0.024 - 0.079Sz + 0.042Lt - 0.018Lt^2 - 0.031SzLt \quad (2)$$

With an Adjusted R^2 of 83.8%

$$Dim_y = 0.01 - 0.053Sz + 0.058Lt - 0.016Lt^2 + 0.013v - 0.0313SzLt \quad (3)$$

With an Adjusted R^2 of 86.9%

$$Dim_z = 0.152 + 0.042Lt \quad (4)$$

With an Adjusted R^2 of 2.8%

Analyzing the first two equations, the Adjusted R^2 is high, with the main difference being that the response along the Y axis is influenced by printing speed which does not happen to the X axis, possibly due to a quirk in either the RSM or the printer itself. Given this difference in equations, the difference in response is quite low, although the real deviations in Y are closer to the predicted values. The geometric deviations in Z have an Adjusted R^2 of 2.8%, which means that the equation is not a good predictor of the response. The causes are mainly due to how 3d printers work. Namely, since the printer has to find 0, where the print bed is, a small change in this value is bound to change the deviations. Furthermore, other effects such as layer compression, non-orthogonality between the print bed and the Z axis, and non-planar print bed, can also cause problems. Finally, in cases where the tuning of the 0 point is done manually, as is the case with the printer used, is possibly the biggest contributor to Z variations, which can be seen in table 6 for the Center point repetitions.

Finally, in all tested specimens there is no clear pattern to the deviations, with some being positive, others negative, sometimes in the same batch of specimens, with the exception of larger parts where the deviations are always negative. The tolerance falls between IT9 and IT12 in the X and Y directions, and over IT14 for the Z direction. These tolerances are within the expected values for pre-processed polymer parts, which has an impact in the guidelines.

3.4. Guidelines

With these tests Guidelines for FDM regarding surface roughness and geometric deviations can be given.

Regarding improving surface roughness:

Parts should ideally be a collection of rectangular prisms and should be orientated such as the biggest surface area is on the print bed, since it provides the smallest value of R_a .

Chamfers should be used at 45° whenever possible, instead of fillets, for a constant R_a , since the equations predict an equal value in all directions of the chamfer.

Parts with curved faces should have those faces printed vertically (90°) to ensure constant surface roughness.

Cylinders should be printed vertical for the best possible values of surface roughness.

Layer height should be as small as possible.

If any face is angled with any other face, the part should be positioned, insuring the angled surface is at least at 45° or higher for the best results.

Figure 5 shows a part with all of the above considerations.

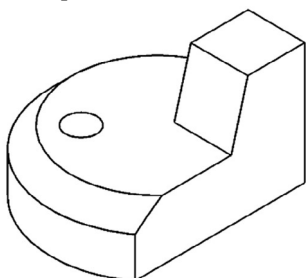


Figure 5 – Example of a part using the guidelines

Regarding dimensional variation:

For the least variation, important surfaces should be perpendicular to the XoY plane.

For a more controlled variation part dimensions should be somewhat large.

If accuracy is important the Z axis should be avoided for those accurate measurements.

Parts to be printed should be designed to be printed larger than the nominal dimensions due to the fact that most variations are negative, which also allows that, if dimensional accuracy would have to be improved, below the IT9 measured, post processing is a necessity.

4. Conclusions

This study aimed to obtain predicting equations for surface roughness and dimensional tolerances for parts produced by FDM, and to develop guidelines for Design for Additive Manufacturing. The results show that only a few of the printing parameters have a statistically significant influence on the response, with the prediction equations show good adjusted R^2 values, except for the dimensional variation in the Z axis.

This also allowed for the determination of the surface roughness and dimensional variation, for any given value of the influencing parameters.

The predicting equations confirmed that the best orientations for surface roughness are 0° or 90° although it was somewhat surprising to discover that the R_a at 90° is smaller than at 0° . At low angles of orientation, the staircase effect is much more prevalent than at higher angles, resulting in higher roughness. Dimensionally the study showed that in the Z axis, a correct bed leveling and setup is of paramount importance, and that the 3d printer was relatively similar values of dimensional variation in the XoY plane.

The development of the predicting equations also allowed the development of a number of guidelines to improve surface roughness and Dimensional tolerances, furthering the knowledge of DfAM.

Acknowledgements

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Appendix A. Screening experiment

Table 5 – DoE results for RSM (surface Roughness)

Test n°	Inputs			Responses
	Lt [mm]	V [mm/s]	θ [°]	R_a [μm]
1	0.07	25	15	7.101
2	0.13	25	15	11.117
3	0.07	75	15	6.557
4	0.13	75	15	9.233

5	0.07	25	75	14.224
6	0.13	25	75	21.383
7	0.07	75	75	15.262
8	0.13	75	75	22.934
9	0.05	50	45	9.452
10	0.15	50	45	19.715
11	0.1	8	45	14.440
12	0.1	92	45	14.029
13	0.1	50	-5	14.485
14	0.1	50	95	7.317
15	0.1	50	45	16.199

Table 6 – DoE results for RSM (Deviations)

Test n°	Inputs				Responses		
	Sz [mm]	Lt [mm]	v [mm/s]	T [°C]	Dim X [mm]	Dim Y[mm]	Dim Z[mm]
1	20	0.2	70	215	0.18	0.17	0.29
2	50	0.2	70	215	0.07	0.03	0.35
3	20	0.1	70	215	0.04	0.01	0.14
4	50	0.1	70	215	0.16	0.11	0.16
5	20	0.2	30	215	0.11	0.14	0.34
6	50	0.2	30	215	0.14	0.11	0.38
7	20	0.1	30	215	0.01	0.04	0.12
8	50	0.1	30	215	0.15	0.12	0.1
9	20	0.2	70	205	0.11	0.15	0.29
10	50	0.2	70	205	0.16	0.04	0.24
11	20	0.1	70	205	0.05	0.04	0.13
12	50	0.1	70	205	0.19	0.08	0.15
13	20	0.2	30	205	0.07	0.12	0.33
14	50	0.2	30	205	0.15	0.02	0.37
15	20	0.1	30	205	0.07	0.07	0.12
16	50	0.1	30	205	0.17	0.11	0.14
17	5	0.15	50	210	0.01	0.01	0.02
18	65	0.15	50	210	0.2	0.1	0.19
19	35	0.05	50	210	0.16	0.17	0.15
20	35	0.25	50	210	0.05	0.05	0.23
21	35	0.15	10	210	0.07	0.02	0.15
22	35	0.15	90	210	0.07	0.03	0.09
23	35	0.15	50	200	0.09	0.03	0.16
24	35	0.15	50	220	0.07	0.04	0.15
25*	35	0.15	50	210	0.01	0.02	0.06
26*	35	0.15	50	210	0.04	0.02	0.2
27*	35	0.15	50	210	0.02	0	0.11
28*	35	0.15	50	210	0.05	0	0.3
29*	35	0.15	50	210	0	0.01	0.09

*Center point repetitions

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