Robust design application for optimizing ABS fused filament fabrication process: A case study

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Abstract. The current paper is a case study of optimizing fused filament fabrication (FFF) process using robust design. FFF process is a low cost 3d printing process that uses ABS (Acrylonitrile-Butadiene-Styrene) filament in order to build progressive layer by layer, physical prototypes. Four (4) parameters having three levels each ones is used (Deposition angle, Layer thickness, Infill ratio, Infill pattern). The quality indicator that used for the optimization process is the dimensional accuracy. It was found that the layer thickness is the most important parameter in the reported experimental area.

1. Introduction

Fused Filament Fabrication (FFF) also known as Fused Deposition Modeling (FDM) is a 3D printing technique that uses melted plastic filament in order to build physical models layer by layer [1]. Nowadays, FFF process characterized as a low cost 3D printing process and it can be used at a plethora of applications [2]. Figure 1 shows the FFF process [3].

Due to the increased demand for low cost prototypes as well as small batches of durable finished plastic products, FFF process became one the most attractive digital manufacturing processes. The main advantages of this technology are the simplicity of the whole procedure, the open source software, the material availability and the cost of the equipment. One the other hand, quality issues are the main obstacles for this technology. Usually, a lot of trials are needed in order to build acceptable final physical models [4].

Figure 1. FFF 3D printing process [3]. Figure 2. Zortax M200 3d printer.
Many researchers have studied the influence of a variety of process parameters on dimensional accuracy of parts produced using the FFF/FDM method. Mahmood et al. [5] used Taguchi’s L$_{27}$ orthogonal array in order to study the effect of 13 process parameters among which are: Infill pattern, layer thickness and infill density. They found out that the parameters which affect more the dimensional accuracy in descending order are: Floor/roof thickness, infill speed, infill pattern, outline speed, inset speed, platform temperature and layer thickness. Hyndhavi et al. [6] studied the influence of layer thickness, raster angle and build orientation on the dimensional accuracy of specimens fabricated using both ABS and PLA of FDM process. The results showed that raster angle and build orientation are the parameters that highly influence the dimensional accuracy of the parts of both materials.

In this research a case study is presented in order to optimise process performance of a low cost 3D printer. Process parameters and experimental area are selected according to the 3D printer specification, bibliography and experience. The main purpose was to achieve good quality 3D printing final parts. Dimensional accuracy selected as the performance quality measure for this optimization.

2. Equipment and material description
In this work the Zortax M200 3D printer is used (see figure 2). Build volume of 3D printer is 200 mm x 200 mm x 180 mm in X, Y and Z axis respectively. Also, the layer resolution ranges between 90 to 390 microns. ABS material is used for building the models. Dimensional accuracy measurements were performed by a digital caliper with a 0.001 mm accuracy.

Nine (9) test parts were built using Robust Design [6-12]. Then dimensional accuracy was measured and analysed using data analysis tools (ANOM and ANOVA). Figure 3 shows the nine experimental specimens as well as figure 4 shows quality issues of the FFF process. The dimensions that measured were the base of the test part, X direction is the length of the test part, Y direction is its width and Z direction is its height. The nominal dimensions of the part are 35 mm at X direction, 15 mm at Y direction and 10 mm at Z direction. The dimensional error of the measured dimensions from the nominal dimensions was calculated and the results were used for the dimensional accuracy analysis.

![Figure 3. Test parts.](image1)

![Figure 4. Quality issues of FFF printed specimen.](image2)

3. Experiment set up
Taguchi Robust design was used for the experimental procedure [8]. Process parameters (control factors) and the corresponding levels are shown in table 1. For all experiments printing temperature was hold at 275 °C, bed temperature at 80 °C, and raster angle at 45°. Nozzle diameter was 0.4 mm as well as material diameter was 1.75 mm. Printing speed of the process is associated with the quality (high for all the experiments).
Table 1. FDM Process parameters.

| Process Parameter | Level 1 | Level 2 | Level 3 |
|-------------------|---------|---------|---------|
| A-Deposition angle (°) | 0       | 15      | 30      |
| B-Layer Thickness (mm) | 0.09    | 0.19    | 0.29    |
| C-Infill ratio (%) | 10      | 20      | 30      |
| D-Infill pattern | Rectangular (R) | Honeycomb (H) | Octagonal (O) |

Taguchi design uses orthogonal arrays in order to perform an experiment. Orthogonality means that all the combinations of the parameter levels appear at each pair of columns of the array [8]. The L9 (3^4) orthogonal array is used as shown in table 2. This array has four columns, one for each process parameter. All experimental and calculation results for the dimensional accuracy can be seen at table 3.

Table 2. Taguchi orthogonal array L9 (3^4).

| Number of experiment | Deposition angle (°) | Layer thickness (mm) | Infill ratio (%) | Infill pattern |
|----------------------|----------------------|----------------------|------------------|---------------|
| 1                    | 0                    | 0.09                 | 10               | R             |
| 2                    | 0                    | 0.19                 | 20               | H             |
| 3                    | 0                    | 0.29                 | 30               | O             |
| 4                    | 15                   | 0.09                 | 20               | O             |
| 5                    | 15                   | 0.19                 | 30               | R             |
| 6                    | 15                   | 0.29                 | 10               | H             |
| 7                    | 30                   | 0.09                 | 30               | H             |
| 8                    | 30                   | 0.19                 | 10               | O             |
| 9                    | 30                   | 0.29                 | 20               | R             |

Table 3. Experimental and calculation results.

| No of experiment | Measurements | Nominal Dimension | Dimensional Error |
|------------------|--------------|-------------------|-------------------|
|                  | X (mm)       | Y (mm)            | Z (mm)            | DX (mm) | DY (mm) | DZ (mm) |
| 1                | 34.926       | 15.056            | 10.218            | -0.074  | 0.056   | 0.218   |
| 2                | 34.953       | 15.060            | 10.173            | -0.047  | 0.060   | 0.173   |
| 3                | 34.990       | 15.053            | 10.056            | -0.010  | 0.053   | 0.056   |
| 4                | 34.973       | 15.020            | 10.380            | -0.027  | 0.020   | 0.380   |
| 5                | 34.936       | 15.120            | 10.440            | -0.064  | 0.120   | 0.440   |
| 6                | 35.010       | 15.070            | 10.426            | 0.010   | 0.070   | 0.426   |
| 7                | 34.802       | 14.983            | 10.251            | -0.198  | -0.017  | 0.251   |
| 8                | 34.923       | 15.080            | 10.325            | -0.077  | 0.080   | 0.325   |
| 9                | 34.996       | 15.196            | 10.503            | -0.004  | 0.196   | 0.503   |
| Average          | 34.945       | 15.071            | 10.308            | -0.055  | 0.071   | 0.308   |
4. Data analysis
Refer Minitab software was used for the data analysis. Signal to noise ratio (S/N) was set at the choice of ‘the nominal the best’. The formula of the objective function is the following:

\[ S/N = -10 \cdot \log_{10}(\sigma^2) \]  

(1)

This function is used when we want to base S/N ratio on standard deviation (σ) only. In this case the experimental data can have negative, positive or zero values.

Figure 5 shows the analysis of means (ANOM) diagrams for the four (4) process parameters of the dimensional error in X, Y and Z directions. Such diagrams are used in order to specify the impact of each parameter on the quality indicators. In addition, ANOM diagrams can be used for the selection of the best levels of each process parameter. For example, the most important parameter for the dimensional error at X direction is the layer thickness and level 3 (0.29 mm) minimizes that error.

Figure 5. ANOM diagrams (Error DX, DY, and DZ).
Analysis of variance (ANOVA) is the other tool that is used to quantify the impact of each factor onto the quality indicators. In this study, regression analysis was used along with ANOVA in order to fully examine how process indicators affect dimensional error. F and P values were calculated for the regression and all the factors. The parameter with the greatest F value is considered the most important. P value is used to weigh the strength of the evidence. A P value smaller than 0.05 implies significance. \( R^2 \) value was also calculated. This value is useful for interpreting the results of a statistical analysis; it represents the percentage of variation in a response. Table 4 summarises all the results for the X, Y and Z directions.

Table 4. ANOVA and \( R^2 \) results.

| X axis - Dimensional error (mm) | DF | SS  | MS  | F-Value | P-Value |
|-------------------------------|----|-----|-----|---------|---------|
| Regression                    | 5  | 0.02369 | 0.00474 | 1.93  | 0.313   |
| Deposition angle              | 1  | 0.00365 | 0.00365 | 1.48  | 0.310   |
| Layer thickness               | 1  | 0.01450 | 0.01451 | 5.89  | 0.094   |
| Infill ratio                  | 1  | 0.00286 | 0.00286 | 1.16  | 0.360   |
| Infill pattern                | 2  | 0.00267 | 0.00134 | 0.54  | 0.629   |
| Error                         | 3  | 0.00738 | 0.00261 |  |  |
| Total                         | 8  | 0.03107 |  |  |  |

\[ R^2 \] 76.24%

| Y axis - Dimensional error (mm) | DF | SS  | MS  | F-Value | P-Value |
|-------------------------------|----|-----|-----|---------|---------|
| Regression                    | 5  | 0.02599 | 0.00520 | 4.98  | 0.108   |
| Deposition angle              | 1  | 0.00135 | 0.00135 | 1.29  | 0.338   |
| Layer thickness               | 1  | 0.01127 | 0.01127 | 10.80 | 0.046   |
| Infill ratio                  | 1  | 0.00042 | 0.00042 | 0.40  | 0.572   |
| Infill pattern                | 2  | 0.01296 | 0.00648 | 6.21  | 0.086   |
| Error                         | 3  | 0.00313 | 0.00104 |  |  |
| Total                         | 8  | 0.02912 |  |  |  |

\[ R^2 \] 71.35%

| Z axis - Dimensional error (mm) | DF | SS  | MS  | F-Value | P-Value |
|-------------------------------|----|-----|-----|---------|---------|
| Regression                    | 5  | 0.10727 | 0.02145 | 1.06  | 0.514   |
| Deposition angle              | 1  | 0.06657 | 0.06657 | 3.29  | 0.167   |
| Layer thickness               | 1  | 0.00308 | 0.00308 | 0.15  | 0.722   |
| Infill ratio                  | 1  | 0.00821 | 0.00821 | 0.41  | 0.569   |
| Infill pattern                | 2  | 0.02941 | 0.01470 | 0.73  | 0.553   |
| Error                         | 3  | 0.06065 | 0.02022 |  |  |
| Total                         | 8  | 0.16792 |  |  |  |

\[ R^2 \] 63.88%
5. Results and conclusions
In this research, Robust design is used for optimizing the quality performance of FFF process. Taguchi orthogonal array L9 is selected having four parameters and three levels for each parameter. Deposition angle, layer thickness, infill ratio and infill pattern are used for design purposes. After the analysis of the results, the following findings are summarized: i) Layer thickness is the most important factor for the X and Y direction dimensional error. The F value is 5.89 and 10.80 for X and Y respectively. Z direction is not affected by layer thickness, ii) The most important factor for the Z direction is the deposition angle (F = 3.29). This parameter is not so important for the X direction (F = 1.48) and totally unimportant for Y direction (F = 1.29), iii) The combination that optimizes dimensional error in X direction is (A2B3C2D3), where A is the deposition angle, B the layer thickness, C the infill ratio, and D the infill pattern, iv) The combination that optimize error in Y direction is (A1B1C3D2), v) The combination that optimize error in Z direction is (A1B1C3D3), vi) The values 0° for deposition angle, 0.09 mm for layer thickness and 30% for infill ratio optimize dimensional accuracy in Y and Z axes. Also, the same results are observed in X and Z direction when the infill pattern is set to octagonal.

The investigation of more process parameters onto the quality performance of the FFF process is proposed as a possible future work. This is useful in order to eliminate the number of trials for achieving final prototypes of good quality. It is also suggested the investigation of other quality performance indicators, such as surface roughness. Surface roughness is studied in previous work [10] and was found that when temperature increased the surface quality increased, too.

References
[1] Kruth JP, Leu MC, Nakagawa T 1998 CIRP Annals 47 525-540
[2] Yan X, Gu P 1996 Comp.-Aided Des. 28 307-318
[3] Moza Z, Kitsakis K, Kechagias J, Mastorakis N 2015 Optimizing dimensional accuracy of fused filament fabrication using taguchi design Proc. of the 14th Int. Conf. on Instrumentation, Measurement, Circuits and Systems (Salern: Italy) p 110
[4] Dimitrov D, Wijck WV, Schreve K and Beer ND 2006 Rap. Protot. Journ. 12 42-52
[5] Mahmooda S, Qureshib AJ, Talamonac D 2018 Addit. Manuf. 21 183-190
[6] Hyndhavia D, Babub GR, Murthy SB 2018 Mat. Tod.: Proc. 5 23508–23517
[7] Kechagias J 2007 Rap. Protot. Journ. 13 316-323
[8] Phadke MS 1995 Quality engineering using robust design Prentice Hall PTR
[9] Kitsakis K, Alabey P, Kechagias J, Vaxevanidis NA 2016 IOP Conf. Ser.: Mater. Sci. Eng. 161 012025
[10] Chaidas D, Kitsakis K, Kechagias J, Maropoulos S 2016 IOP Conf. Ser.: Mater. Sci. Eng. 161 012033
[11] Kitsakis K, Kechagias J, Vaxevanidis N, Giakopoulos D 2015 IOP Conf. Ser.: Mater. Sci. Eng. 161 012024
[12] Kitsakis K, Kechagias J, Vaxevanidis N, Giakopoulos D 2016 Acad. J. of Manuf. Engin. 14 4