3D Printer parameters analysis for PCL/PLA filament wire using Design of Experiment (DOE)

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Abstract: Fabrication of medical implant using composite Polycaprolactone (PCL)/ Polylactic Acid (PLA) through a process of fused filament fabrication (FFF) is the future of medical field. In this study the capabilities of FFF process and optimization of the Parameter was investigated to achieve the 20mm x 20mm x 10mm dimensional accuracy of printed composite material. Design of experiment using technique full factorial with two level design is used to study the interaction of factor which is print temperature (A), height of deposition (B), print speed (C) and travel speed (D). By using DOE, the total 20 run include with 4 center point was investigated by extruding the composite material using 3D printer. The dimension accuracy is tested using flexible measuring machine. From the sample, the ANOVA analysis of variance is divided into 3 responses, length, width and height. Factor model A, C and BD show the significant effect on length and for width response, factor model effected the dimensional accuracy is A, C, AC, and AD. Meanwhile for height respond only factor model A and C show the significant effect on the respond. Based on the analysis, one optimum parameter run is selected among ten of the suggested run. The optimum parameter value consists of 136°C print temperature, 0.12mm deposition of height, 20mm/s printing speed and 22mm/s travel speed. The confirmation run analysis this optimum parameter shows the precise dimension with average margin error below that 15% for length, width and height respond.

Keywords: Fused filament fabrication (FFF); Design of experiment (DOE); PCL; PLA; FDM

1. Introduction

In the past few years, 3D printing technology is growing rapidly. The ability of this technology allows fabrication of custom-made implant and medical devices, suddenly realize the world about the potential of this technology for biomedical field. Additive manufacturing had becoming a new technology that provides crucial impact on biomedical implant. This technology gives an opportunity to customized implant according to the specific patient [1][5].

Before additive manufacturing had been introduced to the biomedical implant fabrication, the previous method was using the conventional process. The conventional process is too complicated due to much fabrication stage but only for a single implant. This typical process involves several steps such as taking images for the tissues, produce mold, calculating for the tissue geometry and even machining using Computer numerical control machine. This conventional process is time consuming and increased the price tag for the implant [2].

Since the introduction of additive manufacturing for fabricating biomedical implant, the process become easier, low cost, less time consuming and it enable directly customized implant for the patient. However, this immature technology has substantial challenges in term of type of material and material printed capability using 3D printer. To solve the problem regarding this technology, several studies need to be done in term of new type of material composite and printed capability for the new material using 3D printer. Currently a composite material called
Polycaprolactone (PCL) / Polylactic acid (PLA) is a choice for the implant material.

In medical implant fabrication, the material must be biocompatible and capable to undergoing reaction under physiological condition of body. From the properties of material, Polycaprolactone (PCL) / Polylactic Acid (PLA) composite have the characteristic that suitable for human implant [3]. Despite this composite excellent in term of characteristic, the major problem is the optimization process parameter using 3D printer. The parameter setting such as, print temperature and feed rate have direct influence on the printed capabilities for this composite.

Beside optimization process parameter, the main issue regarding this composite is the printed accuracy for producing implant. Every medical device such as implant needs accuracy in dimension. The accuracy of dimension related to the precision in term of extrusion of the material and parameter setting [4][6]. This work focuses on study in optimization parameter of PCL/PLA material in term of print temperature, deposition height, print speed and travel speed by using 3D printer. The dimensional accuracy was analyzed based on replication sample 20mm x 20mm x 10mm.

2.0 Methodology

2.1 Material Fabrication

Material fabrication is the procedure for preparation the composite material PCL/PLA before the fused filament fabrication process begins by using extrusion process. The processing material is based on extruding the filament using single screw extruder, cooling it using water bath and pull it using pulling roller to get the constant size of filament. The objective of this process is to produce the material filament in range of 1.75 mm to 1.8 mm diameter. Figure 1 below shows the picture of machine use for fabrication of material.

![Figure 1: Material fabrication setup](image-url)
2.2 Designing and printing sample

Designing the sample is first step in fused filament fabrication process. For designing the sample CAD software is needed to drawn 2 x 2 x 1 cm (20 x 20 x 10 mm) cube. Using this software, the CAD model are converted to STL file before the file converted to G-Code file. Figure 2(a) shows the CAD model draw using Solidwork 2014 with dimension unit mm. Next, the test sample is fabricated using FlashForge creator pro 2016 machine. Figure 2(b) shows the 3D printer use in this study.

![Sample cube 20mm x 20mm x 10mm drawn using Solidwork 2014.](image)

![FlashForge Creator Pro machine.](image)

Figure 2: (a) Sample cube 20mm x 20mm x 10mm drawn using Solidwork 2014. (b) FlashForge Creator Pro machine.

2.3 Design of experiment (DOE)

Design expert software version 10 has been use as an aided software to analysis the parameter. In this experiment full factorial with 2 level of factor studies and 4 center point block has been choose to run experiment. By using 4 factor with 3 respond which is length, width and height the total run is 16 run based on 2x2x2x2. However, because 4 center point block, the total run will be 20 run. From the literature review, the range of the factor is tabulated in Table 1.

| No. | Parameter                      | Low level | High level |
|-----|--------------------------------|-----------|------------|
| 1.  | Print temperature (°C)         | 130       | 160        |
| 2.  | Height of deposition (mm)      | 0.1       | 0.2        |
| 3.  | Printing speed (mm/s)          | 20        | 50         |
| 4.  | Travel speed (mm/s)            | 20        | 50         |
2.4 Dimensional Accuracy

After the printing process using FFF 3D printer. The dimensional accuracy need to be tested in order to find the best variable that produce the most accurate printed model. To test the dimensional accuracy for printed model 2 x 2 x 1 cm cube, Flexible measuring machine Mitutoyo QM353.

3.0 Results and Discussion

3.1 Result on collected respond data

According to the Table 2 below, 4 factor which is print temperature, height of deposition, printing speed and travel speed is represent as factor 1, factor 2, factor 3 and factor 4. While for the respond which is length, width and height is represent as respond 1, respond 2 and respond 3. From the respond data, the data shows run number 3 is the best dimensional accuracy according the cube model dimension 20 mm x 20mm x 10. Data response measured is tabulated as shown in Table 2.

| No of Run | Factor 1 Print temperature (°C) | Factor 2 Height of deposition (°C) | Factor 3 Printing speed (mm/s) | Factor 4 Travel speed (mm/s) | Response 1 Length (mm) | Response 2 Width (mm) | Response 3 Height (mm) |
|-----------|---------------------------------|-----------------------------------|-------------------------------|---------------------------|----------------------|----------------------|----------------------|
| 1         | 160                             | 0.1                               | 50                            | 20                        | 16.4398              | 17.9482              | 10.5260              |
| 2         | 160                             | 0.2                               | 50                            | 50                        | 13.9620              | 16.8902              | 10.5804              |
| 3         | 130                             | 0.1                               | 20                            | 20                        | 19.9835              | 20.0280              | 10.2245              |
| 4         | 145                             | 0.15                              | 35                            | 35                        | 18.8990              | 19.3878              | 10.4840              |
| 5         | 145                             | 0.15                              | 35                            | 35                        | 17.9098              | 18.5875              | 10.4525              |
| 6         | 145                             | 0.15                              | 35                            | 35                        | 19.2025              | 20.0735              | 10.5732              |
| 7         | 160                             | 0.1                               | 50                            | 50                        | 18.5384              | 16.8374              | 10.4906              |
| 8         | 130                             | 0.1                               | 20                            | 50                        | 19.9365              | 20.0735              | 10.3735              |
| 9         | 160                             | 0.2                               | 20                            | 50                        | 16.8490              | 16.7901              | 10.5582              |
| 10        | 130                             | 0.2                               | 50                            | 20                        | 19.8275              | 19.5895              | 10.604               |
| 11        | 130                             | 0.2                               | 20                            | 20                        | 20.1790              | 20.0775              | 10.2985              |
| 12        | 160                             | 0.2                               | 20                            | 20                        | 19.5435              | 19.8735              | 10.5395              |
| 13        | 160                             | 0.2                               | 50                            | 20                        | 16.3263              | 18.7967              | 10.5745              |
| 14        | 130                             | 0.2                               | 50                            | 50                        | 17.8035              | 20.1085              | 10.5435              |
| 15        | 145                             | 0.15                              | 35                            | 35                        | 19.1024              | 20.0845              | 10.6530              |
| 16        | 160                             | 0.1                               | 20                            | 20                        | 17.6525              | 19.6920              | 10.4968              |
| 17        | 130                             | 0.1                               | 50                            | 50                        | 18.8510              | 20.0410              | 10.6865              |
| 18        | 130                             | 0.1                               | 50                            | 20                        | 19.3800              | 19.9385              | 10.5865              |
| 19        | 160                             | 0.1                               | 20                            | 50                        | 19.6870              | 19.9880              | 10.4880              |
| 20        | 130                             | 0.2                               | 20                            | 50                        | 20.0780              | 20.0460              | 10.4750              |

3.2 Surface Morphology

From the experiment, there were certain inconsistencies and error happens due to the incorrect
parameters that resulted to a damaged printed part. Figure 3(a) shows the effect of gap between infill and outline. In 3D printing the printed part is created by combining the layer infill and the parameter outline. Typically, in the standard printing process the infill layer is printed faster than the parameter outline. Because of this step of process, the layer infill need to have much time to bond with the parameter outline. From the morphology analysis on 20 printed sample, several sample with higher printed speed is effected on this defect.

A part from that, the effect of stringing or oozing is shown in Figure 3(b). Stringing effect occur because of the extruder temperature is too high when printing part using FFF 3D printer. If the temperature is too high the material become less viscous and will leak from nozzle during the retraction. For this experiment only higher temperature with higher travel speed are effected from this defect.

Figure 3: (a) Gap between infill and outline effect; (b) Stringing or oozing effect

Figure 4(a) shows the effect of overheating on the printed sample. Overheating effect occur because of the print temperature is not suitable with the material. When the material extruded from the nozzle, it must achieve the correct balance between temperature of nozzle and the cooling time of the extruded part. However, in this case, the material did not have the right balance of cooling time. This problem happens on run with high temperature for example run number 1 and number 2.

Meanwhile, Figure 4(b) shows the effect of rough corner and warping. Rough corner issue typically occurs because of the material not cooled quickly. Meanwhile for warping issue, the problem always pointed on bed temperature problem. In this experiment, the rough corner were detected on every sample. This defect occurs because of PCL/PLA composite take a lot of time to cool or solidified due to its material properties. For warping issue, the problem occurs because during the experiment the heated bed platform are off due to the low temperature of PCL [7][8].

Figure 4: (a) Overheating Effect; (b) Rough corner and warping effect
3.3 Analysis of Length response

Figure 5 shows the half normal plot graph for length response analysis. From the plotted graph, the significant model effect which are point A, C, BD has been selected for the next evaluation using analysis of variance and Table 3 summarize the data of ANOVA analysis for length response.

![Half Normal Plot](image)

**Figure 5:** Half normal plot graph for length response

**Table 3:** ANNOVA analysis for length response

| Source                  | Sum of squares | df | Mean Square  | F Value | Prob>F |
|-------------------------|----------------|----|--------------|---------|--------|
| Model                   | 38.57          | 5  | 7.72         | 9.41    | 0.0006 * |
| A-print temperature     | 18.15          | 1  | 18.15        | 22.14   | 0.0004 |
| B-Deposition of height  | 2.18           | 1  | 2.18         | 2.65    | 0.1272 |
| C-Print Speed           | 10.21          | 1  | 10.21        | 12.46   | 0.0037 |
| D-travel speed          | 0.82           | 1  | 0.82         | 1.00    | 0.3349 |
| BD                      | 7.21           | 1  | 7.21         | 8.80    | 0.0109 |
| Curvature               | 0.37           | 1  | 0.37         | 0.45    | 0.5152 |
| Residual                | 10.66          | 13 | 0.82         |         |        |
| Lack of Fit             | 9.60           | 10 | 0.96         | 2.73    | 0.2208 ** |
| Pure error              | 1.05           | 3  | 0.35         |         |        |
| Cor Total               | 49.59          | 19 |              |         |        |

*significant  * non-significant  **

From the ANOVA analysis the model F–value of 9.41 implies the model is significant. Beside that there are only 0.06% chance that an F-value this large could occur due to noise. In
this case model A, C, and BD are significant model term because the values of Prob>F less than 0.0500. However, the other model B and D is insignificant model because the value of Prob>F is large than 0.0500.

For the curvature F value is 0.45 implies the non-significant value. From the table it shows that there are 50% chance a Curvature F value this large could occur noise. In other analysis part, the “lack of Fit F-value” of 2.73 implies the lack of fit is non-significant relative to the pure error. Chance that a lack of fit F-value this large could occur due to noise is only 22.08%. However, the non-significant lack of fit is still good.

3.4 Analysis of width response

Figure 6 shows the half normal plot graph for width response analysis. From the plotted graph the significant model effect which are point A, C, AC and AD and Table 4 summarize the data of ANOVA analysis for width response.

![Half-Normal Plot](image)

Figure 6: Half normal plot graph for width response

| Table 4: ANOVA analysis for width response |
|------------------------------------------------|
| **Response**: Width | **ANOVA for selected factorial model** |
| **Analysis for variance table (Partial sum of square)** |  |
| **Source** | **Sum of squares** | **df** | **Mean Square** | **F Value** | **Prob>F** |
| Model | 19.31 | 5 | 3.86 | 7.05 | 0.0022* |
| A-print temperature | 10.70 | 1 | 10.70 | 19.54 | 0.0007 |
| C-Print speed | 2.57 | 1 | 2.57 | 2.57 | 0.0493 |
| D-Travel speed | 1.67 | 1 | 1.67 | 3.05 | 0.1043 |
| AC | 1.77 | 1 | 1.77 | 3.23 | 0.0954 |
| AD | 2.59 | 1 | 2.59 | 4.73 | 0.0486 |
| Curvature | 0.42 | 1 | 0.42 | 0.77 | 0.3957 |
| Residual | 7.12 | 13 | 0.55 |  |  |
| Lack of Fit | 5.61 | 10 | 0.56 | 1.11 | 0.5244** |
| Pure error | 1.51 | 3 | 0.50 |  |  |
| Cor Total | 26.85 | 19 |  |  |  |
3.5 Analysis of height response

The value of height response has been analyzed and interpreted using a half normal plot. Figure 7 shows the half normal plot graph for height response analysis. From the plotted graph the significant model effect which are point C, A and AC has been selected for the next evaluation using analysis of variance. However, point A model is automatically listed because to support the hierarchy. After selecting the model, the next step focused to the analysis of Variance ANOVA. Table 5 summarize the data of ANOVA analysis.

![Half-normal Plot](image)

**Figure 7:** Half normal plot graph for width response

**Table 5:** ANOVA analysis of variance table for height response

| Source         | Sum of squares | df | Mean Square | F Value | Prob>F   |
|----------------|----------------|----|-------------|---------|----------|
| Model          | 0.15           | 3  | 0.051       | 9.66    | 0.0009*  |
| A-print temperature | 0.013        | 1  | 0.013       | 2.54    | 0.1315   |
| C-Print speed  | 0.081          | 1  | 0.081       | 15.44   | 0.0013   |
| AC             | 0.058          | 1  | 0.058       | 10.99   | 0.0047   |
| Curvature      | 0.004572       | 1  | 0.004572    | 0.87    | 0.3651   |
| Residual       | 0.079          | 15 | 0.005242    |         |          |
| Lack of Fit    | 0.054          | 12 | 0.004498    | 0.55    | 0.8042** |
| Pure error     | 0.025          | 3  | 0.008221    |         |          |
| Cor Total      | 0.24           | 19 |             |         |          |

3.6 Confirmation run

For confirmation run, suggested optimum run was repeated 5 time in order to verify the optimum
parameter setting for PCL/PLA 3D printed cube by using fuse filament fabrication process. By using Flashprint software, the printed temperature are set to 136°C, deposition of height 0.12 mm, print speed 20mm/s and travel speed 22mm/s. In order to get the eligible test, the result from actual versus theoretical test must be in the margin of error less than 15%. From Figure 8 below, it can be seen that all the average error recorded for the length, width and height are below 15% which is acceptable.

**Figure 8:** Confirmation run result for (a) length, (b) width and (c) height

| Run | Length of PCL/PLA 3D printed sample | Actual (mm) | Predicted (mm) | Error (%) |
|-----|-------------------------------------|-------------|----------------|-----------|
| 1   |                                     | 19.985      | 20.000         | 0.0075    |
| 2   |                                     | 20.025      | 20.000         | 0.025     |
| 3   |                                     | 19.9470     | 20.000         | 0.025     |
| 4   |                                     | 19.985      | 20.000         | 0.025     |
| 5   |                                     | 20.025      | 20.000         | 0.025     |

Average error (%) 0.2102

| Run | Length of PCL/PLA 3D printed sample | Actual (mm) | Predicted (mm) | Error (%) |
|-----|-------------------------------------|-------------|----------------|-----------|
| 1   |                                     | 20.0760     | 20.000         | 0.360     |
| 2   |                                     | 20.0990     | 20.000         | 0.045     |
| 3   |                                     | 20.0270     | 20.000         | 0.135     |
| 4   |                                     | 20.0470     | 20.000         | 0.235     |
| 5   |                                     | 20.0610     | 20.000         | 0.505     |

Average error (%) 0.220

4.0 Conclusion

From this studies a sample size 2 x 2 x 2 cm in cube are successfully printed from PCL/PLA composites material using Fused Deposition Modelling (FDM) method with the aid of DOE. From the experiment, Analyzed of Variance (ANOVA) for length response, the significant effect that have been identified are print temperature (A), print speed (C) and interaction between deposition of height with travel speed (BD). Meanwhile for width response, the significant effect that have been identified are print temperature (A), print speed (C), interaction of print temperature with print speed (AC) and interaction of print temperature with travel speed (AD). For the height response, the significant effect are print temperature (A), print speed (C) and interaction of print temperature with print speed (AC). From combining analysis, the most significant effect that influence the dimensional accuracy of the PCL/PLA printed sample are print temperature and print speed. From the confirmation run the optimize parameter has been tested is 136°C print temperature, 0.12mm deposition of height, 20mm/s print speed and 22mm/s travel speed and by measuring the optimize parameter dimension, the value of error are below than 15% which is acceptable. This prove that PCL/PLA biocomposite can be printed using additive manufacturing technique. Further work have to be carried out in order to achieve the perfect printed part.
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