Optimization of process parameters in fused filament fabrication (FFF) utilizing poly lactic acid (PLA)

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Abstract. This research was to find an optimum parameter in Fused Deposition Modelling, FDM. They are various type of printing parameter in 3D printing. The parameter that was focused on in this research are orientation, print head and layer thickness while other parameters will be fixed. This parameter was evaluated the mechanical properties of the printed parts. The mechanical properties will be performed on the specimen are tensile test and 3 point-bending tests. The data were analyzed using Taguchi’s Method with orthogonal array of 9 level and Analysis of Variance, ANOVA. The highest of ultimate tensile strength was 34 MPa where the parameter were 34.592 MPa. The highest of flexural strength was 95.542 MPa. The optimum parameter for the tensile test was 25-degree of orientation, 0.4 mm of print head and 0.2 for layer thickness. The optimum parameter for 3-point-bending test was 0-degree of orientation, 0.4 mm of print head and 0.15 mm of layer thickness. This parameter did the mechanical test again for the validation test. The average ultimate tensile strength value for 25-degree of orientation, 0.4 mm of print head and 0.2 for layer thickness was 30.558 MPa. While the average of flexural strength for 0-degree of orientation, 0.4 mm of print head and 0.15 mm of layer thickness was 95.557 MPa.

1. Introduction
Additive manufacturing is the technology that produce 3 dimensional part via printing. This technology had already seen vast development and research done for the past few years [1]. These technologies are known to be independence from geometric constraints [2]. Fused filament fabrication (FFF) is one of the additive manufacturing systems that show an excellence work with reliable cost alternative in additive manufacturing [3]. There is various type of material used in FFF these days in 3-dimensional printing such as acrylonitrile butadiene styrene (ABS) and poly lactic acid (PLA). This material can be used as a filament to be extruded from the nozzle that had been heated and produce 3D objects layer by layer from bottom to the top. Poly lactic acid is the preferable material for prototyping or as master pattern in casting since it is easy to print and have excellent mechanical properties as compare to other plastic except composite material [4].

Additive manufacturing (AM) creates three-dimensional (3D) physical objects by the aid of computer-aided design (CAD) software [5]. The process of 3-dimensional printing is by melting and extruding material which creating an object in a layer by layer manner to form 3-dimensional objects [6]. On the other hand, the additive manufacturing provides the technique in an efficient way to make the complicated geometries at a shorter produce of time cycle and in lower of cost [7]. Furthermore, this technology is broadly used in engineering to custom the prototype, pre-surgical models, functional models and conceptual models [8].
2. Methodology
2.1. Differential Scanning Calorimetry
Differential scanning calorimetry analysis of the filament was conducted under 0.833 mL/s of nitrogen gas flow by using DSC Q10 from instrument of Thermal Analysis. The poly-lactic acid sample was weighted about 5 mg. Then, the sample was put into the aluminium pan before put into the thermal analysis machine.

2.2. Printing setup
Ideamaker was used to set-up the varied parameters of print head, orientation and layer thickness prior to the printing process. The others parameter which are not considered their effect to the mechanical properties in this study are set as default value. The varied values for print head, orientation and layer thickness are identified by bench marking on finding of previous researchers. The values were then being used to set on the Ideamaker software [5]. The geometrical solid CAD were saved in Standard Tessellation Language (STL) file format where 3D printer can read the format. Some common adjustment are needed by the STL file to fix the size, orientation and position to test the specimen after printing [9]. Ideamaker is the software had an adjustment and decoded the G-Code. 45 samples of dog-bone shape samples were printed and 45 samples of rectangular bar were printed respectively.

2.3. Tensile test and 3-point-bending test
Two mechanical tests were carried out to determine the structural behavior of the specimen which are tensile test and 3-point-bending test. The mechanical test were conducted using AG-IS Shimadzu Universal Testing Machine. Five samples were tested and the tensile strength or flexural strength values were averaged for each level. For each mechanical test, nine level are to be set based on Taguchi’s orthogonal array of 9 Level. Based on the bending test standard ASTM D790, the thermoplastic (Poly-Lactic Acid, PLA) is set at support-span-to-depth ratio of 16:1. The speed of the tensile test at constant rate of 83.3 μm/s. Meanwhile the speed of 3-Point Bending test was taking at 33.3 μm/s [10] [11].

2.4. Analysis of Variance (ANOVA) and Pooling Technique
By taking the data from Table 3 and Table 4, the ANOVA analysis of the important of all major and their relations by comparing the mean square against the evaluated specific confident levels of an estimate of the experimental error. Pooling is usual practice of disregarding of the influence of the column where the consideration are not significant. When the error of Degree of Freedom is non-zero, the test for performance could be performed. However, pooling method should start with the weakest factor.

3. Results and discussion
3.1 Differential Scanning Calorimetry
By referring the Figure 1, it is observed that at the first heat, a glass transition temperature are around 56 °C. From this point, that the properties of the mechanical test of the Poly-Lactic acid is changed from elastic material to brittle material. This is due to when chain movement is changed. Then, the cold crystallization is started around 83.75 °C and the melting temperature is about 129.43°C. However, for second heat for this Poly-Lactic Acid sample with a rate of 10 °C/min, shows that there is no evidence of the glass transition temperature, cold crystallization temperature and the peak of the melting temperature.

3.2 Tensile test
It is observed the high of ultimate tensile stress is 34.592 MPa. The combination of printing parameter are 25 degree of orientation, 0.2 millimetre of print head and 0.15 millimetre of layer thickness. Table 1 shows that parameter ranking for mean of Signal-to-Noise ratio for tensile test. It can be observed that the combination of optimum parameter are level 2 in orientation, level 3 in print head and level 3 for layer thickness. Figure 2 until figure 4 show the level of orientation, the level of print head and the level of layer thickness.
Figure 1: DSC graph

Table 1: Parameter ranking for mean of Signal-to-Noise ratio for tensile test

| Parameters    | Level 1 (dB) | Level 2 (dB) | Level 3 (dB) | Main effect | Rank |
|---------------|--------------|--------------|--------------|-------------|------|
| Orientation   | 25.686       | 27.898       | 26.790       | 2.212       | 2    |
| Print Head    | 24.965       | 26.427       | 26.540       | 4.279       | 1    |
| Layer Thickness| 26.790       | 26.540       | 27.310       | 0.770       | 3    |

3.3 3-point-bending test

The highest value of the flexural strength produce was 94.577 MPa. The combination of the parameter was 45-degree in orientation, 0.4 millimeter of the print head and 0.1 millimeter of the layer thickness. Table 2 shows that parameter ranking for a mean of Signal-to-Noise ratio for 3-point-bending test. Figure 5 until figure 7 shows that the level of orientation, the level of print head and the level of layer thickness.

Table 2: Parameter ranking for a mean of Signal-to-Noise ratio for 3-point-bending test
Parameter | Level 1 (dB) | Level 2 (dB) | Level 3 (dB) | Main Effect | Rank  
--- | --- | --- | --- | --- | ---  
Orientation | 37.6659 | 35.3741 | 36.5409 | 2.2920 | 2  
Print Head | 35.1782 | 36.0703 | 38.3324 | 3.1542 | 1  
Layer Thickness | 36.9900 | 37.5442 | 37.2516 | 1.7074 | 3  

### 3.4 Data analysis using Analysis of Variance

#### Table 3: ANOVA for Tensile test

| Source        | DF | Adj SS  | Adj MS  | F-Value | P-Value | Contribution (%) |
|---------------|----|---------|---------|---------|---------|------------------|
| Orientation   | 2  | 7.4757  | 3.738   | 0.51    | 0.663   | 14.52            |
| Print Head    | 2  | 28.381  | 14.190  | 1.93    | 0.341   | 55.14            |
| Layer Thickness | 2  | 0.923   | 0.461   | 0.06    | 0.941   | 1.79             |
| Error         | 2  | 14.6866 | 7.343   |         |         |                  |
| Total         | 8  | 51.467  |         |         |         |                  |

It can be observed from the Table 3, the print head contributes the most toward the effect of tensile strength at 55.14% compared to orientation where the contribution value is 14.52%. Layer thickness gives the lowest contribution value of 1.79%. As the layer thickness pooled, confidence interval of main effect cannot be calculated. Layer thickness in this case is considered as not significant, the performance at optimum condition cannot be estimated. Therefore, the printing process parameters which are orientation, print head and layer thickness were not optimized.

#### Table 4: ANOVA for 3-Point-Bending test

| Source        | DF | Adj SS  | Adj MS  | F-Value | P-Value | Contribution (%) |
|---------------|----|---------|---------|---------|---------|------------------|
| Orientation   | 2  | 14.044  | 7.022   | 4.91    | 0.169   | 34.55            |
| Print Head    | 2  | 15.861  | 7.931   | 5.55    | 0.153   | 39.02            |
| Layer Thickness | 2  | 7.879  | 3.939   | 2.76    | 0.266   | 19.38            |
| Error         | 2  | 2.858   | 1.429   |         |         |                  |
| Total         | 8  | 40.642  |         |         |         |                  |

It can be observed from Table 4, print head gives contributes the most toward the effect of flexural strength at value of 39.02% compares to orientation where the contribution value is 34.55%. Layer thickness gives the lowest contribution value of 19.38%. Since layer thickness pooled, the confidence interval of the main effect cannot be calculated. Layer thickness in this case is considered as not significant, the performance at optimum condition was not estimated. Therefore, the processing parameter which are orientation, print head and layer thickness were not optimized.

To solve these issues, first, the machine needs to be calibrated in term of alignment of the print bed. This is because the alignment of the print bed was not stable. Dwell small variation of print head and layer thickness, the post-print bed platform is sensitive to the outcome of printed sample. Next, the value of the varied parameter which are orientation, print head, and layer thickness must be reidentified. These value which had been set in table 3 based on previous researchers are not suitable to be setting in the experiment where it leads unable to pool the weakest factor that is layer thickness. Table 5 shows the suggestion parameter which helps to get the significant optimum parameter.

#### Table 5: Printing parameters with level

| Parameters          | Levels  |
|---------------------|---------|
|                     | 1       | 2 | 3 |
| Orientation         | 0°      | 25° | 45° |
| Print Head          | 0.2 mm  | 0.3 mm | 0.4 mm |
| Layer thickness (mm)| 0.1 mm  | 0.15 mm | 0.2 mm |
After that, the software which been used must be changed from Ideamaker to Cura. This is because the g-code generated by different software might produce different layer-by-layer of the printed nozzle. Then, the temperature of the nozzle must be changed from 200°C to 201°C. The temperature difference was 1°C. However, from this different of values, it could change the error of the printing process where it leads to getting to significant optimum process parameters. Furthermore, 5 samples taken on each level must be changed to 6. This is because the more sample taken to do the mechanical test will produce accurately the data.

4. Conclusion
In conclusion, the objectives of this research had achieved which are to evaluate the mechanical properties of polylactic acid for Fused Filament Fabrication, FFF printed parts, to investigate the optimum printing parameter.

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