Printing temperature, printing speed and raster angle variation effect in fused filament fabrication

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Abstract. Additive Manufacturing becomes most widely uses in prototyping and production applications since 3D printer becomes as open-source. However, there are not provide standard value of printing process parameters to give best performance of mechanical properties of the printed parts. In additional, printed parts produced can be affected by the various parameters used, this nature of phenomena very complex. The purpose of this research is to evaluate the effects printing process parameters respond to its mechanical properties in tensile strength and flexural strength from Fused Filament Fabrication by using Polylactic Acid (PLA) with printing parameters, namely printing temperature, printing speed and raster angle. The specimens were printed by using Monoprice Maker Select 3D printer. Tensile test and three-point bending test were carried out. Taguchi Method involves in identification of proper control factors to obtain the optimum results of the process. Orthogonal Arrays (OA) are used to conduct a set of experiments. Results of these experiments analyze by using Analysis of Variance (ANOVA) to predict the quality of components produced and find influence of printing temperature, printing speed and raster angle on mechanical properties. The results show that raster angle have most influence on both mechanical properties with 68.72% contribution, printing speed 18.88% and temperature 1.49% contribution in tensile test while for bending test raster angle obtain 94.02% contribution, printing speed give 2.28% and temperature only 1.67% contribution. Optimum value obtain for tensile test in this study shows temperature = 180ºC, printing speed = 40 mm/s, and raster angle = 60º. In bending test gives temperature = 185ºC, printing speed = 30 mm/s, and raster angle = 60º.

1. Introduction

The manufacture of part using FFF processes is subjected to numerous variables dependent upon thermophysical and/or chemical phenomena that are going to result in parts with different characteristics depending on the method used along with the parameters of the process. The nature of these phenomena is very complex, as they are also affected by the influence of related environmental and process conditions; for example, if the process is performed within a controlled atmosphere, the existence (or the lack thereof) of a heated bed and/or the heat transmission process affects the thermal gradients of the workpiece, particularly between layers. This research presents a study influence of the tensile mechanical behaviour of pieces produced using the Fused Filament Fabrication (FFF) additive manufacturing technique with respect to the parameter of printing process with most widely used material polylactide (PLA). The aim of this study is to the evaluate best parameters of printing.
temperature, printing speed and raster angle by optimizing on the mechanical performance of PLA test specimens.

2. Methodology

Material used is Polylactic Acid (PLA). 3D printing machine used is IIIP Monoprice 3D Printing. STL generated from Catia, and change into G code in the IdeaMaker slicer. Table 1 show varied parameter used for set of experiment design for Taguchi optimization method. This set experiment that conducted using Taguchi is appropriate because of their effective method of experiment and more precise. Set of experiment for both tensile and fatigue is show in Table 2. The microscopic structure and porosity of the filament will be analyse using metallurgy microscope. Next, the relationship between the PLA materials are analysed especially the aspect of microscopic structure, mechanical properties and others. The best PLA (specimen filament) parameter will be chosen, in the next step for future work.

| Table 1. Parameter and level |
| Factor | Level 1 | Level 2 | Level 3 | Unit  |
|-------------------|--------|--------|--------|------|
| Printing Speed    | 30     | 35     | 40     | mm/s |
| Printing Temperature | 180   | 185    | 195    | Degree |
| Raster Angle      | -45/45 | 0/90   | 30/60  | degree |

| Table 2. Taguchi table for both tensile and fatigue test |
|---------------------------------|-------------------|-------------------|
| Raster Angle | Printing Speed | Printing Temperature |
|-------------------|--------|-------------------|
| 0/90    | 30     | 180   |
| 0/90    | 35     | 185   |
| 0/90    | 40     | 190   |
| -45/45  | 30     | 190   |
| -45/45  | 35     | 180   |
| -45/45  | 40     | 185   |
| 30/60   | 30     | 185   |
| 30/60   | 35     | 190   |
| 30/60   | 40     | 180   |

90 samples were fabricated for tensile and flexural test. ASTM D638 and ASTM D790 [17][18] used to decide the geometry, velocity, load and procedure are followed. Tensile test is conducted by utilizing Shimadzu Universal Testing machine with minimum speed applied is 5 mm/mm and 5kN load. While flexural test was conducted at 2mm/mm speed with 5kN load.

3. Result and Discussion

3.1 Result for Tensile and Flexural Test

After the tensile and flexural tests are conducted the data obtained are recorded in Table 3 and Table 4. The highest tensile yield strength is 23.16MPa from level 3 with -45/45 raster angle, 40mm/s printing speed and 190-degree printing temperature. While the lowest (level 8) with printing parameter are set at 30/60 raster angle, 35mm/s printing speed and 190-degree printing temperature. The highest flexural yield strength is level 5 with 0/90 raster angle, 35mm/s printing diameter and 185-degree printing temperature with 63.48MPa strength. While the lowest is at level 8 similar to the tensile lowest level.
Table 3. Data of Tensile Strength

| Exp No | Ultimate Tensile Strength (MPa) | Average (MPa) |
|--------|---------------------------------|---------------|
| 1      | 12.38 16.30 15.93 16.10 13.64  | 14.87         |
| 2      | 16.79 15.44 16.42 15.20 17.25  | 16.22         |
| 3      | 23.78 23.03 22.67 22.80 23.52  | 23.16*        |
| 4      | 17.10 15.40 15.20 16.00 17.80  | 16.30         |
| 5      | 19.85 20.47 19.20 21.11 20.17  | 20.16         |
| 6      | 14.69 13.73 14.83 14.51 13.94  | 14.22         |
| 7      | 16.67 20.10 19.33 17.82 18.03  | 18.39         |
| 8      | 13.86 12.23 10.91 9.73 12.07  | 11.76         |
| 9      | 21.16 21.20 23.16 22.41 22.62  | 22.51         |

Table 4. Data of Flexural Strength

| Exp No | Maximum Force (kN) | Flexural Strength (MPa) |
|--------|--------------------|-------------------------|
| 1      | 0.034 0.025 0.025  | 0.030 0.026 0.028      |
| 2      | 0.050 0.056 0.044  | 0.061 0.039 0.050      |
| 3      | 0.087 0.069 0.072  | 0.085 0.065 0.076      |
| 4      | 0.066 0.047 0.051  | 0.049 0.067 0.056      |
| 5      | 0.094 0.081 0.084  | 0.090 0.081 0.086      |
| 6      | 0.038 0.031 0.013  | 0.032 0.021 0.027      |
| 7      | 0.086 0.091 0.080  | 0.082 0.091 0.086      |
| 8      | 0.023 0.023 0.013  | 0.034 0.035 0.019      |
| 9      | 0.038 0.035 0.044  | 0.040 0.035 0.039      |

Based on the data average value from Table 3 and Table 4, the morphological characteristic shows good interlayer bonding and uniformly distributed struts is the main factor that contributed toward highest tensile and flexural strength. Meanwhile, for medium and lowest tensile and flexural strength are due to the weak bonding of the interlayer and no uniform struts coming out from the nozzle head. This might be due to the unsuitable printing temperature and printing speed set of parameters.

Figure 1: Morphological characteristic of tensile test specimens at varied magnification, A. Highest tensile strength, B. Medium tensile strength, and C. Lowest tensile strength
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Figure 2: Graph of S/N ratio versus level of parameter for tensile test.

Figure 3: Graph of S/N ratio versus level of parameter for flexural test.

From the data obtained, the yield tensile and flexural strength were recorded and the S/N ratio for each level are calculated. The type of S/N ratio is the bigger the better. The optimum parameter for the tensile test is 180-degree printing temperature, 40mm/s printing speed and 30/60-degree raster angle as shown in Figure 1 and Table 5, while optimum parameter for flexural test is 185-degree printing temperature, 30mm/s printing speed and 30/60-degree raster angle as shown in Figure 2 and at Table 6.

| Level | Printing Temperature | Printing Speed | Raster Angle |
|-------|----------------------|----------------|--------------|
| 1     | 180*                 | 30             | -45/45       |
| 2     | 185                  | 35             | 0/90         |
| 3     | 190                  | 40*            | 30/60*       |

Table 5. Response table (Tensile)

| Level | Printing Temperature | Printing Speed | Raster Angle |
|-------|----------------------|----------------|--------------|
| 1     | 180*                 | 30             | -45/45       |
| 2     | 185*                 | 35             | 0/90         |
| 3     | 190                  | 40             | 30/60*       |

Table 6. Response table (Flexural)

3.2 ANOVA Analysis

The most significant parameter is raster angle. The F value for both experiments is higher than f table of 90 confident interval. The experiment not influence by Printing temperature for tensile and fatigue test. Table 7 and Table 8 show the ANOVA table for tensile and fatigue test respectively.

| Source              | DF | Adj SS   | Adj MS   | F-value | P-value | Contribution % |
|---------------------|----|----------|----------|---------|---------|----------------|
| Printing Temperature| 2  | 0.05665  | 0.02822  | 0.14    | 0.880   | 1.49           |
| Printing Speed      | 2  | 0.71690  | 0.35845  | 1.73    | 0.366   | 18.88          |
| Raster Angle        | 2  | 2.60887  | 1.30444  | 6.30    | 0.137   | 68.72          |
| Error               | 2  | 0.41393  | 0.20696  |         |         |                |
| Total               | 8  | 3.79636  |          |         |         |                |

Table 7. ANOVA (Tensile)

| Source              | DF | Adj SS   | Adj MS   | F-value | P-value | Contribution % |
|---------------------|----|----------|----------|---------|---------|----------------|
| Printing Temperature| 2  | 0.2628   | 0.1314   | 0.82    | 0.549   | 1.67           |
| Printing Speed      | 2  | 0.3604   | 0.1802   | 1.13    | 0.471   | 2.28           |
| Raster Angle        | 2  | 14.8392  | 7.4196   | 46.30   | 0.021   | 94.02          |
| Error               | 2  | 0.41393  | 0.2070   |         |         |                |
| Total               | 8  | 3.79636  |          |         |         |                |

Table 8. ANOVA (Flexural)
4. Conclusion

From the result of this research the influence of three parameter and the mechanical test are determined. The result is:

1) The highest tensile yield strength is 23.16MPa from level 3 with -45/45 raster angle, 40mm/s printing speed and 190-degree printing temperature. The highest flexural yield strength is level 5 with 0/90 raster angle, 35mm/s printing diameter and 185-degree printing temperature with 63.48MPa strength.

2) The optimum parameter for the tensile test is 180-degree printing temperature, 40mm/s printing speed and 30/60-degree raster angle while optimum parameter for flexural test is 185-degree printing temperature, 30mm/s printing speed and 30/60-degree raster angle.

3) The most significant printing parameter is raster angle for both tensile and three-point bending test.

4) The printing temperature did not give great influence in the printing parameter and mechanical properties.

5) Other factor for instance air gap, humidity, printing orientation, printing head size, different type of support structure, number of perimeter and another parameter must be considered. So that the information and the result from the testing can be simplified in order to find the standard parameter of 3D printing and desirable quality, lower cost, high mechanical properties in the 3D printing.

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