Mechanical performance of wood poly-lactic acid 3d part under different printing parameter in fused filament fabrication

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Abstract. Mechanical properties of parts from fused filament fabrication has been made known to be directionally dependent or in other word anisotropy. Several common process parameters were varied to study their impact on the mechanical properties, in particular compression and bending strength of the end product in the material of wood PLA. The Taguchi method was used to design and simplify the experiment without compromising the experiment’s efficiency. S/N ratio from Taguchi analysis was interpreted for determining the optimum combination of process parameter for the highest compressive and bending strength. The build orientation angle is the major factor contributing to higher compression and bending strength recorded followed by infill density and lastly layer thickness. The maximum value for compressive stress is 98.9 MPa with 0° built orientation, 0.15mm layer thickness and 60% infill, while for bending stress it is 73.6 MPa with 0° built orientation, 0.20mm layer thickness and 100% infill.

1. Introduction
Fused filament fabrication (FFF) is an additive manufacturing (AM) technology used in the construction of 3D products [1]. In detail, it is a rapid prototyping and production technique that adds molten plastic layer by layer to form a 3D product. FFF also known as fused deposition modeling (FDM). Poly-lactide-acid (PLA) filament is known to be easy to print [2] and because of that, a substantial amount of research work on PLA had been performed. Sood et al. [3], stated the mechanical properties are influenced by layer thickness, orientation, raster angle, raster width and air gap. However, there is a small number of researched involving PLA that is combined with other materials as to alter the mechanical properties. Hence, the research work presented is in this paper is of the mechanical properties for filaments from PLA fused with wood. It presents the effect of print orientation, layer thickness and in-fill density on compressive and flexural strength.

2. Design of Experiment
This research used the Taguchi method of orthogonal array design to study the whole spectrum of the parameter used with reduced number of experiments [4], and was conducted for $L_9$ orthogonal array. Calculation on the degree of freedom (DOF) is necessary before any orthogonal array is chosen to be implemented. The chosen array must have the same or greater number of runs compared to the total DOF calculated. Table 1 show the orthogonal array of $L_9$ used in this research, with 9 experimental runs in this research. The parameter tested were print orientation, layer thickness

and in-fill density with others parameter were set to Ender 3 machine default setting. The experiment was conducted in open environment of the Additive Manufacturing Laboratory. The Wood PLA filaments were obtained from Magma with 20% by weight of real wood powder [5].

### Table 1. Taguchi Model for Experiment Run

| Run | Orientation (angle°) | Layer Thickness (mm) | In-fill Density (%) |
|-----|----------------------|----------------------|--------------------|
| 1   | 0                    | 0.10                 | 60                 |
| 2   | 0                    | 0.15                 | 80                 |
| 3   | 0                    | 0.20                 | 100                |
| 4   | 45                   | 0.10                 | 80                 |
| 5   | 45                   | 0.15                 | 100                |
| 6   | 45                   | 0.20                 | 80                 |
| 7   | 60                   | 0.10                 | 100                |
| 8   | 60                   | 0.15                 | 60                 |
| 9   | 60                   | 0.20                 | 80                 |

### 3. Testing

The compression test was conducted with reference to standard ASTM D695. Table 2 show the result obtained for compression test while Table 3 is the result for bending test. As shown in Table 2, the maximum compression value is 98.9MPa in Run 1, while the intermediate value is 21.1MPa in Run 5 and the minimum compressive stress recorded is 9.6MPa in Run 8. While in Table 3, the maximum, intermediate and minimum value for bending stress is 73.6MPa in Run 3, 49.6MPa in Run 4 and 30.0 MPa in Run 8; respectively.

### Table 2. Tabulated Raw Data of Wood PLA for Compression Test

| Run | Result Compressive Stress (MPa) | Average (MPa) |
|-----|---------------------------------|---------------|
|     | n1     | n2     | n3     | n4     | n5     |
| 1   | 95.4   | 94.7   | **98.9** | 98.1   | 95.9   | 96.6 |
| 2   | 94.7   | 93.8   | 95.0   | 95.1   | 95.3   | 94.8 |
| 3   | 95.0   | 93.9   | 95.7   | 94.9   | 80.4   | 92.0 |
| 4   | 19.5   | 17.3   | 17.6   | 18.2   | 17.8   | 18.1 |
| 5   | 22.2   | 18.9   | **21.1** | 19.9   | 22.9   | 21.0 |
| 6   | 11.6   | 10.2   | 10.2   | 11.0   | 10.3   | 10.7 |
| 7   | 26.5   | 26.5   | 25.7   | 24.0   | 24.8   | 25.5 |
| 8   | 9.9    | **9.6** | 10.3   | 10.5   | 10.6   | 10.2 |
| 9   | 12.6   | 11.1   | 15.7   | 17.3   | 13.9   | 14.1 |

### Table 3. Tabulated Raw Data of Wood PLA for Bending Test

| Run | Result Bending Stress (MPa) | Average (MPa) |
|-----|-----------------------------|---------------|
|     | n1   | n2   | n3   | n4   | n5   |
| 1   | 45.1 | -    | 50.5 | 49.1 | 47.6 | 48.1 |
| 2   | 54.6 | 49.0 | -    | 56.8 | 44.6 | 51.2 |
| 3   | **73.6** | 73.1 | -    | 70.4 | 61.7 | 69.7 |
| 4   | 45.9 | **49.6** | 50.8 | 52.1 | 40.5 | 47.8 |
| 5   | 42.7 | 42.2 | 41.2 | 39.8 | -    | 41.5 |
| 6   | 50.3 | -    | 50.5 | 48.1 | 45.2 | 48.5 |
| 7   | 41.0 | 41.3 | -    | 40.8 | 44.7 | 42.0 |
| 8   | 30.3 | 30.4 | **30.0** | 30.4 | 32.1 | 30.7 |
| 9   | 49.8 | 51.6 | 36.0 | 48.7 | 50.7 | 47.4 |
4. Analysis of Results

Taguchi method uses a statistical measure of performance, called as signal-to-noise (S/N) ratio. The S/N ratio is a logarithmic function of desired output serves as objective functions for optimization. The S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). This ratio is a measure of robustness used to identify control factors that reduce variability in a product or process by minimizing the effect of uncontrollable as Nominal the best (NB), Lower the better (LB) and Higher the better (HB). The S/N ratio for each quality characteristic can be computed independently and regardless of the category of the performance characteristics. Figure 1 show the result for compression test and bending test.

4.1 ANOVA Calculation for Determining Ultimate Strength

ANOVA is a short for analysis of variances is a statistical technique for testing if three or more population means are equal. In this research, to support the S/N plot, ANOVA tables are developed and show the percentage influences of the factor for the compression test (Table 4) and bending test (Table 5).

![Figure 1. Compression S/N Plot and Bending S/N Plot.](image)

### Table 4. ANOVA Table for Compression Test

| Parameter | Factor        | Degree of Freedom (DOF) | Sum of Square ($S^2_n$) | Variance ($V^2_n$) | F-ratio | Contribution (%) |
|-----------|---------------|-------------------------|-------------------------|-------------------|---------|-----------------|
| A         | Orientation   | 2                       | 486.65                  | 243.32            | 125.08  | 89.64           |
| B         | Layer Thickness | 2                       | 17.86                   | 8.93              | 4.59    | 2.59            |
| C         | Infill Density | 2                       | 30.15                   | 15.07             | 7.75    | 4.88            |
| Error     | -             | 2                       | 3.89                    | 1.94              | -       | 2.89            |
| Total     | -             | 8                       | 538.56                  | -                 | -       | 100             |

### Table 5. ANOVA Table for Bending Test

| Parameter | Factor        | Degree of Freedom (DOF) | Sum of Square ($S^2_n$) | Variance ($V^2_n$) | F-ratio | Contribution (%) |
|-----------|---------------|-------------------------|-------------------------|-------------------|---------|-----------------|
| A         | Orientation   | 2                       | 13.54                   | 6.77              | 115.29  | 47.61           |
| B         | Layer Thickness | 2                       | 10.22                   | 5.11              | 87.01   | 35.83           |
| C         | Infill Density | 2                       | 4.31                    | 2.15              | 36.76   | 14.90           |
| Error     | -             | 2                       | 0.11                    | 0.058             | -       | 1.66            |
| Total     | -             | 8                       | 28.20                   | -                 | -       | 100             |
4.2 Scanning Electron Microscope (SEM) Analysis

SEM was used in this research to analyse the surface morphology of failure. Both Torrado et al. and Sood et al. utilized SEM to analyse fracture surface of the 3D printed specimens to provide a vision to the mode of failure [6] and to have a clear image of air gap and void between raster extruded for the study in the dimensional accuracy of FDM parts [4]. The SEM results in Figure 4 to Figure 21 showed the microstructure at the surface of failure for compression and bending test. The specimens with highest, intermediate and lowest charted compression and bending strength are inspected. As aforementioned in Table 2, the specimen for compression test with the lowest properties is specimen number 8.2 (Figure 2, 3, & 4) followed by 5.3(Figure 5, 6, & 7) for the intermediate and 1.3(Figure 8, 9, & 10) for the highest respectively. Whereas in Table 3, the lowest bending or flexural strength scored is specimen number 8.3, while 4.2 for the intermediate and 3.1 for the highest. In compression test, the specimen fractured at an angle of 60° and 45° (Figure 4 and 5) which are similar to the build orientation used to print the specimen. Due to a lower bond between raster and with significantly larger and more air gap formed (Figure 3 & 4), specimen 8.4 has the lowest compressive strength as compared to specimen 5.3 (Figure 6 & 7) and 1.3 (Figure 9 & 10).

![Figure 2. Fracture of Specimen 8.2](image2.png)
![Figure 3. x50 Zoom](image3.png)
![Figure 4. x100 Zoom](image4.png)

![Figure 5. Fracture of Specimen 5.3](image5.png)
![Figure 6. x50 Zoom](image6.png)
![Figure 7. x100 Zoom](image7.png)

![Figure 8. Fracture of Specimen 1.3](image8.png)
![Figure 9. x50 Zoom](image9.png)
![Figure 10. x100 Zoom](image10.png)

![Figure 11. Fracture of Specimen 8.3](image11.png)
![Figure 12. x50 Zoom](image12.png)
![Figure 13. x100 Zoom](image13.png)
5. Conclusion
In regards to the highest compression and bending strength for wood PLA, it is apparent through to the S/N ratio plot, the build orientation angle is the major factor contributing to higher compression and bending strength recorded followed by infill density and lastly layer thickness. A drastic increase of compression and flexural strength is being observed when the specimen was printed at 0° angle of build orientation with an in-fill density is being increased from 60% to 100%, due to the decrease in void formation and air gap in between raster which contribute to the higher bonding surface of the adjacent raster, thus increase load-bearing area. As for the layer thickness on compression and bending strength, there are not much different trend between both experimental. Despite of the significance, wood PLA charted highest in both compression and bending strength when printed in a 0° manner. On the subject of build orientation, wood PLA had a same optimum printing condition in both experimental. Both compression and strength test set, the strength is decreasing by increasing the build orientation angle from 0° angle to 60°.

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