Optimise 3D printing parameter on the mechanical performance of PLA-wood fused filament fabrication

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Abstract. The effect of printing parameter of tensile and compression specimens on production cost and mechanical performance of the material which is PLA with 20% wood content had been identified. The printing parameters selected are nozzle temperature, raster angle and printing speed. The raster angle and printing speed shows higher impact of tensile specimen on production cost while compression specimen only printing speed. Furthermore, for tensile experiment, raster angle gives highest impact than other parameter while for compression experiment each printing parameter giving an equal reaction to mechanical performance. By plotting the S/N ratio graph, higher nozzle temperature, lower raster angle and printing speed show the optimum printing parameters for tensile specimen. While optimum printing parameters for compression specimen are lower nozzle temperature, higher raster angle and printing speed.

1. Introduction
Additive manufacturing (AM) is the technology used to build 3D objects where the joining process of material was added layer by layer such in fused filament fabrication (FFF). There are many types of polymer that used in FFF which common material are ABS and PLA [1]. Thermoplastic is usually used in additive manufacturing because of the unique physicochemical properties and characteristic such as low cost, light weight, easy to fabricate and variability of compositions [2]. Yedige Tlegenov et al. [3], the lower nozzle temperature had tended to clog more than higher nozzle temperature. K. G. Jaya Christiyanto et al. [4] state the tensile strength will be increase as well as the printing speed decrease. Lastly, Y. Wang et al. [5] state the higher raster angle will lower tensile strength. These three printing parameters gave highly impact for mechanical performance of the material. Based on literature reviews, there are many studies about pure PLA and ABS but still less study about composite material which mixed particularly with PLA or ABS. Most current study on literatures or experiments finding about how printing parameter affect to mechanical performance of pure PLA and ABS. Lastly, the literatures or experiments of the pass usually were about 3D printing to find on printing parameter effect in mechanical performance but not on production cost.

2. Methodology
This experiment will focus on characterizing tensile and compression strength of fused filament fabrication parts produced with PLA with 20% content of wood powder utilizing open source 3D printing software. The addition of 20% wood content increases the modulus of elasticity (MOE) value and reduce the density, any further addition of wood will result in lower MOE values [6]. The printing filament was obtained from Magma3DP and used as it.

2.1. Design of Experiment
To design the experiment, Taguchi method was chosen to simplify the experimental while analysis of variance (ANOVA) was used to determine the influence of each printing parameter on each mechanical property. The selected parameter was list in the table which shown in Table 1 before conducting Taguchi method.
Table 1: Selected printing parameter

| Printing Parameter | Value          |
|--------------------|----------------|
| Nozzle temperature (°C) | 195, 205, 215 |
| Raster angle (°)       | 0, 45, 60     |
| Printing speed (mm/s)  | 30, 40, 50    |

Taguchi table being plotted after identify the selected printing parameters which is shown in Table 2. There are nine levels for each testing (tensile and compression) according to Taguchi L₉.

Table 2: Taguchi model for experiment

| Level | Nozzle Temperature (°C) | Raster Angle (°) | Printing Speed (mm/s) | No. of specimens |
|-------|-------------------------|-----------------|-----------------------|------------------|
| 1     | 195                     | 0               | 30                    | 5                |
| 2     | 195                     | 45              | 40                    | 5                |
| 3     | 195                     | 60              | 50                    | 5                |
| 4     | 205                     | 0               | 40                    | 5                |
| 5     | 205                     | 60              | 50                    | 5                |
| 6     | 205                     | 45              | 30                    | 5                |
| 7     | 215                     | 0               | 50                    | 5                |
| 8     | 215                     | 45              | 30                    | 5                |
| 9     | 215                     | 60              | 40                    | 5                |

2.2. 3D printing specimens

The 3D model be designed using CATIA V5 software by referring ASTM standard [7] [8] for tensile and compression dimension and testing specification. Then the CAD translated to STL file in order to slice the 3D printing software. The tensile and compression specimens were printed based on Taguchi table. The material that used is particle reinforced polymer composite which is PLA with 20% wood content.

2.3. Mechanical Testing and Scanning Electron Microscope (SEM)

Tensile and compression were tested experimentally using universal testing machine (UTM) which namely as SHIMADZU AG-100kN. An UTM machine has maximum 100kN of load and been set up constantly with 2 mm/min of speed for all tensile specimens while 5 mm/min for all compression specimens. SEM had been utilized during fracture surface analysis of 3D printed specimens to provide a vision to the failure mode by using SEM machine from HITACHI TM3000.

3. Result and Discussion

3.1. Tensile Strength

Based from Table 3, the highest average of ultimate tensile stress is level 8 which have 215°C of nozzle temperature, 45° of raster angle and 30 mm/s of printing speed. The circle plotted which shown in Figure 1 is S/N ratio of larger the better as the optimum for each printing parameter. The optimum tensile specimen for printing parameter of nozzle temperature, raster angle and printing speed are 215°C, 0° and 30 mm/s.

3.2. Compression Strength

Based from Table 4, the highest average of maximum compression stress is level 3 which have 195°C of nozzle temperature, 60° of raster angle and 50 mm/s of printing speed. The circle plotted which shown in Figure 2 is S/N ratio of larger the better as the optimum for each printing parameter. The optimum compression specimen for printing parameter of nozzle temperature, raster angle and printing speed are 195°C, 60° and 50 mm/s.
Table 3: Tabulated raw data of tensile test

| Level | Ultimate Tensile Strength (MPa) | Average (MPa) | S/N ratio |
|-------|----------------------------------|---------------|-----------|
| 1     | 12.92067                        | 12.54519      | 11.71875  | 13.82212  | 13.52163  | 12.905672 (Middle) | 22.2156 |
| 2     | 11.64375                        | 13.22115      | 12.31971  | 11.64375  | 11.94389  | 12.15447       | 21.6947 |
| 3     | 9.390144                        | 11.49351      | 12.54519  | 12.54519  | 12.99567  | 11.79394       | 21.4332 |
| 4     | 13.14615                        | 13.29639      | 13.44639  | 12.84567  | 12.31971  | 13.01086       | 22.2861 |
| 5     | 13.14615                        | 13.14615      | 13.14615  | 12.54519  | 12.92067  | 12.98086       | 22.2661 |
| 6     | 12.09447                        | 11.56851      | 11.86899  | 11.79375  | 11.64375  | 11.79389       | 21.4330 |
| 7     | 12.16947                        | 12.46995      | 13.22115  | 13.59688  | 12.99567  | 12.89062       | 22.2055 |
| 8     | 13.14615                        | 13.29639      | 13.89736  | 13.07091  | 13.14615  | 13.31139 (Highest) | 22.4845 |
| 9     | 11.79375                        | 11.79375      | 12.09447  | 11.41827  | 11.49531  | 11.71875 (Lowest) | 21.3776 |

Figure 1: Tensile S/N plot for each printing parameter

3.3 Scanning Electron Microscope Result
As aforementioned, microstructure of specimens for tensile test and compression were inspected with
the highest properties which is level 8.3 for tensile specimen and level 3.5 for compression specimen.

3.3.1 SEM of Tensile and Compression Specimens
In Figure 3, the breaking areas of every layer showed that the specimen had been made with 45°/45°
of raster angle making the specimen stronger among other. Thus, the higher nozzle temperature and
slower printing speed which are 215°C and 30 mm/s occur stronger bonding with layer by layer. This
is because the contact area of each layer is bigger than other printing parameter.
Table 4: Tabulated raw data of compression test

| Level | Maximum Compression Strength (MPa) | Average (MPa) | S/N ratio |
|-------|-----------------------------------|---------------|-----------|
|       | 1  | 2       | 3  | 4      | 5  |       |
| 1     | 96.5054 | 96.8014 | 96.0120 | 96.3574 | 96.4314 | 96.42152 | 39.6835 |
| 2     | 95.3953 | 96.1847 | 99.4164 | 96.1107 | 96.2587 | 96.67316 | 39.7061 |
| 3     | 100.650 | 96.3081 | 99.2437 | 98.2322 | 100.551 | **98.997** (Highest) | 39.9124 |
| 4     | 95.4940 | 94.9019 | 91.3249 | 98.2076 | 96.3327 | 95.25222 (Lowest) | 39.5775 |
| 5     | 95.9380 | 95.4940 | 95.8640 | 99.0957 | 95.5186 | 96.38206 | 39.6799 |
| 6     | 95.9380 | 95.1239 | 96.1600 | 97.6402 | 96.1354 | 96.1995 (middle) | 39.6635 |
| 7     | 95.8640 | 95.3706 | 96.2587 | 96.8261 | 96.2834 | 96.12056 | 39.6563 |
| 8     | 94.5072 | 95.3706 | 96.0860 | 95.2473 | 95.9133 | 95.42488 | 39.5932 |
| 9     | 95.9133 | 95.6913 | 95.5186 | 97.6895 | 96.4561 | 96.25376 | 39.6684 |

Figure 2: Compression S/N plot for each printing parameter

Figure 3: Highest strength of tensile specimen

Figure 4: Highest strength of compression specimen
In Figure 4, the printing conditions gave the highest strength; however, tension break occurred due to failure of the strength that have a higher air gap which is maximum at 201µm. The higher size of air gap is proof that the stress occurred is higher stress.

4. Conclusion

The relationship between printing parameter and mechanical performance showed a good significant effect especially for tensile test where the raster angle is most influencing the printing parameter to the mechanical performance of specimen and also easily can be detected by using SEM for validate the result obtain. The research finding show consistency with others similar research [9-11]. For this research, the optimum printing parameters of PLA with wood content material for tensile strength are at 215°C of nozzle temperature, 0° of raster angle and 30 mm/s of printing speed. While the optimum printing parameters for compression strength are at 195°C of nozzle temperature, 60° of raster angle and 50 mm/s of printing speed. Thus, PLA with wood content can be used in scope of application area same as pure PLA such as medical tool, household item, architecture and engineering models, automotive prototype, and others.

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