COMPARISON STUDY ON MECHANICAL PROPERTIES OF 3D PRINTED PLA AND PLA/ALUMINIUM COMPOSITES USING FUSED DEPOSITION MODELING METHOD

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Abstract. 3D printing technology has been developed to produce prototype and end used parts. The demand is increasing recently making this technology a popular choice for the industry especially using fused deposition modeling (FDM) method. A common material used for this FDM technology is polylactic acid (PLA) as it is sustainable, low cost, and compatible with the system. However new PLA-based composites need to be developed with improved mechanical properties for specific applications. The need to study the mechanical properties and effect of printing parameters on the printed parts of different materials is essential to achieve the desired output. This study intends to apply Taguchi's design of experiment (DOE) method to compare the effect of printing parameters such as layer thickness, number of shell and printing speed on the tensile strength of PLA and PLA/Aluminium composite. The result shows that PLA exhibits better tensile performance compared to PLA/Aluminium composite. The ANOVA analysis also shows that increasing number of shells contribute to greater tensile strength for both materials.

Keywords: fused deposition modeling, tensile strength, and PLA/Aluminium.

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Introduction

3D printing is also known as additive manufacturing (AM) is a well-known manufacturing process and popular in a variety of industries nowadays. The process involves creating and making an object as an initial prototype before commercialization or as a final product [1]. AM technology can be divided into three major categories which are powder-based, liquid-based, and solid-based [2]. One of the methods in liquid-based used in AM to cure the photopolymer liquid, stereolithography (SLA) was invented by Hull in 1986 [3]. Other AM techniques melts the materials in successive layers such as selective laser melting (SLM) and fused deposition modeling (FDM) or soften the materials such as selective laser sintering (SLS) [4-5]. Among these technologies, FDM is the popular choice among the user especially after the patent of this technology has expired.

FDM process is performed by melting the filament in a controlled nozzle head and depositing each layer on a printing platform to develop the complete part [6]. FDM is considered as one of the most recognised AM processes, and it covers a massive part of AM industries market [7-8]. In 2010, Stratasys recorded 3.5 times sales, and some companies' market price increased dramatically, such as Fortus with market price between $100,000 to $500,000 and Beijing Yinhua (products sold with price between $10,000 to $72,000) [9].

Acrylonitrile-butadiene-styrene (ABS) and polylactic acid (PLA) are highly utilised materials in FDM processing. Comparing these two materials, PLA, or aliphatic polyester, is recommended since it provides more advantages than ABS. PLA is made up of low-cost material (corns), which makes polyester is regarded as a highly sustainable product. Lactic acid undergoes a natural condensation process to produce PLA, which involves a polymerisation process that turns the substances into high-molecular-weight polymers [10]. With the advancement of technology, more modification and new materials such as ceramics, composites, and metals are being produced to complement the existing applications. Along with implementing the FDM process, printing parameters should be studied to enhance the printing process of composite materials, which can contribute to the success of the process [11].

Several studies have been conducted to understand and enhance the FDM process's usage by analysing the printed parts' mechanical characteristics [12–16]. Most studies were performed by applying the design of experiment (DOE) method to reduce the error during the experiment [17]. DOE study via the Taguchi method requires a low number of experiments and yet is very effective in determining the significant factors [18]. Thus, the Taguchi method has been widely used by researchers to study the FDM printing parameters in finding the optimum setting to optimise the output of the printed parts.

Although FDM is promoted as the primary selection to manufacture 3D models, the quality and performance of the parts printed from the FDM technique are still questionable since it does not yet reach the industry's standard. Past research highlighted the need to improve the process by analysing and comparing the significant deviation of parts printed by FDM and CAD design [17]. Previous studies tested several parameters that might influence the process, which impacts the mechanical properties of the final product. Among the parameters studied by the past research is the orientation of the parts and infill percentage, which significantly affect the strength of tensile and compression of the printed parts [18]. Other studies also mentioned the analysis on improving the properties by studying the impact of printing parameters and precise adjustment on Young's modulus and tensile strength [12]. Other than that, there are a few research investigated the application of PLA composite with Fe addition

(PLA-5%Fe) which resulted in higher tensile strength in comparison with the pure PLA [19]. From the same perspective, other research justified that there is a lower tensile strength of PLA/Carbon composite in contrast to the usage of pure PLA because of the effect from the carbon structure [20].

Based on previous studies, it is essential to investigate the mechanical performance of different materials with different printing parameters using FDM to suit specific applications. This present study applies the Taguchi DOE approach to investigate the effects of various printing parameters particularly layer thickness, number of shell and printing speed on the tensile strength of PLA and PLA/Aluminium composite. The outcome will be useful to provide an understanding of material performance printed by FDM technology.

Materials and Methods

Design of Experiment (DOE). The design of experiment (DOE) was performed using Minitab 18.0 (Minitab, USA) software and the Taguchi procedure was applied in 3^3 for two materials and resulting in a total of 18 samples. The printing parameters involved in this study can be seen in Table 1. Printing parameters were controlled and specified using ideaMaker Software (Raise3D, USA). For this study, some printing parameters were kept constant and defined as follows:

- printing temperature: 200 ˚C (Recommended by supplier),
- infill percentage: 50%,
- bead temperature: 70 ˚C (Recommended by supplier),
- raster angle: 45˚

Table 1. Printing parameters for sample fabrication.

Level	1	2	3
Layer Thickness (mm)	0.1	0.2	0.3
No of Shell	3	5	7
Printing Speed (mm/s)	30	60	90

Sample fabrication. Test samples were printed using Artillery Sidewinder X1 desktop 3D printer with 1.75 mm diameter filament of PLA and PLA/Aluminium (3D Aura) composite. The PLA/Aluminium is composed of 30% aluminium particulates and 70% PLA. Table 2 shows the 3D printing specifications for Artillery Sidewinder X1.

Table 2. 3D printer specification for Artillery Sidewinder X1.

No.	Items	Specifications
1	Build volume	300 x 300 x 400 mm (11.8 x 11.8 x 15.75 inches)
2	Layer height	0.05 mm.
3	Extruder type	Direct drive.
4	Nozzle type	Volcano.
5	Nozzle size	0.4 mm.
6	Max. extruder temperature	240 °C.
7	Max. heated bed temperature	80 °C.

The sample was designed using Autodesk Inventor Software (Autodesk, USA) based on ASTM test samples (ASTM D638-10 Standard Test Method for Tensile Properties of Plastics) as shown in Figure 1. The general procedure of this test follows the previous study [17].

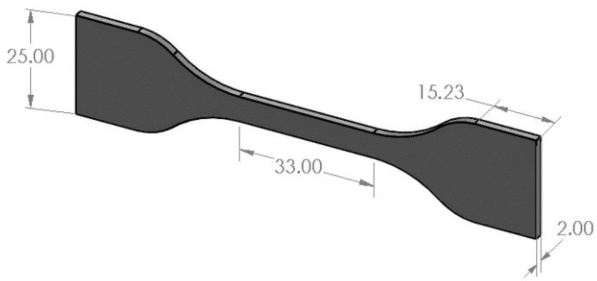
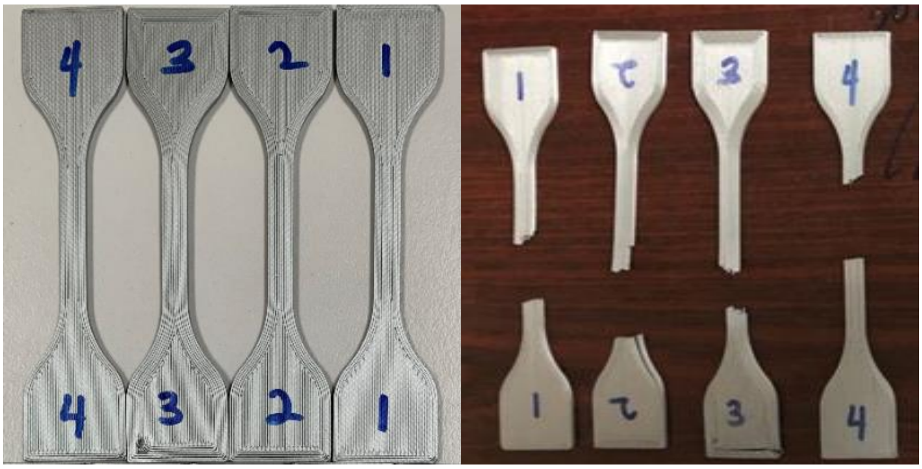


Figure 1. ASTM D638-10 test sample (all dimensions in mm)

Sample testing. The tensile test was performed using tensile test machine LLYOD LR10K plus Universal Tensile Machine. Following the test, a surface texture inspection was performed on the same test area. Since the substance of the specimen was not entirely metal, the printed specimens were coated first using mini sputter coater SC7620, Quorum (UK). The samples structure was examined using Scanning Electron Microscope JSM-IT 100, JEOL Ltd. (Japan). The ultimate tensile strength and tensile samples structure of PLA and PLA/Aluminium composite were then compared.

Results and Discussion

Tensile strength properties. The respective 9 samples of PLA and PLA/Aluminium composite material were successfully printed using Artillery Sidewinder X1 branded FDM-3D printer machine. Figure 2 shows some of the PLA/Aluminium printed samples with different printing parameters before and after the tensile test. Table 3 shows the arrangement of the experimental variables from Taguchi's DOE with tensile strength results for all 18 samples.



(a) **(b)**

Figure 2. Examples of (a) before and (b) after the tensile test for PLA/Aluminium printed samples with different printing parameters

Table 3. The ultimate tensile strength results for PLA and PLA/Aluminum composite

No.	Layer thickness (mm)	No. of shell	Printing speed (mm/s)	Ultimate tensile strength (PLA) (MPa)	Ultimate tensile strength (PLA/Aluminium) (MPa)
1	0.3	3	30	30.184	21.056
2	0.2	5	30	42.476	31.782
3	0.1	7	30	47.723	35.263
4	0.2	3	60	38.042	27.770
5	0.1	5	60	37.944	30.085
6	0.3	7	60	29.352	33.722
7	0.1	3	90	26.989	31.797
8	0.1	5	90	49.278	29.326
9	0.3	7	90	55.089	34.260

Based on the result from Table 3, run number 9 for both PLA/Aluminium and PLA shows the highest ultimate tensile strength (UTS) value which is 34.260 MPa and 55.089 MPa respectively. While run number 1 shows the lowest tensile strength value which is 21.056 MPa and 30.184 MPa respectively. Technically, run number 9 for both materials have maximum stress that can be applied before it breaks. Both material performances were compared, and the graph plot for sample 9 and 1 are shown in Figure 3.

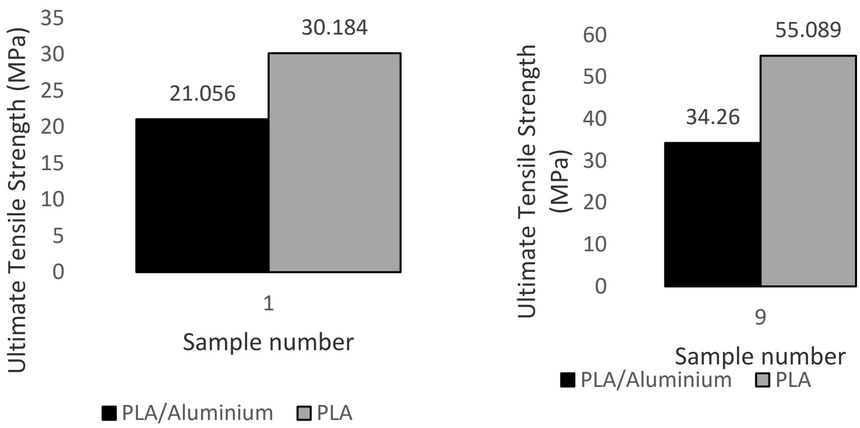
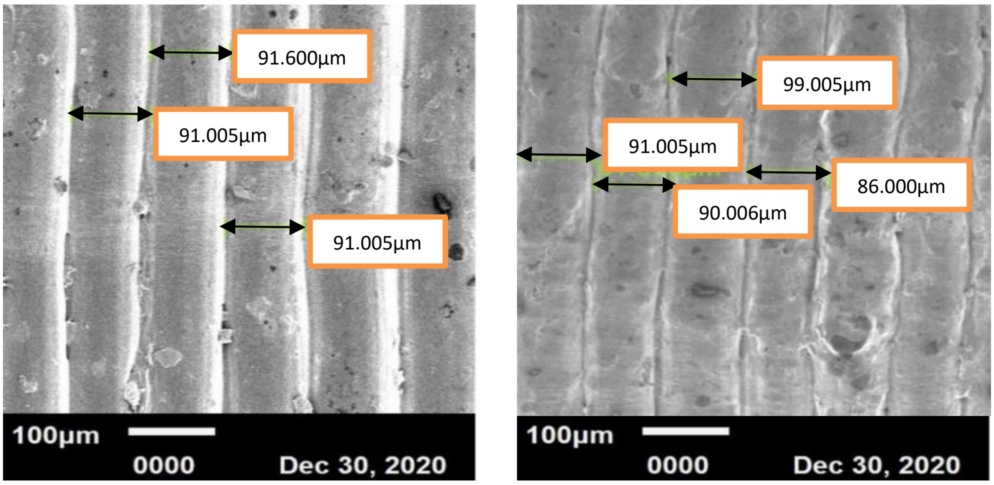


Figure 3. Tensile strength comparison for PLA/Aluminium and PLA on samples 1 and 9.

The results show that the PLA material has superior tensile performance compared to the PLA/Aluminium. Overall, PLA possess more than 20% higher value of tensile strength compared to PLA/Aluminium. The structure for both materials was examined using scanning electron microscopy (SEM). Figure 4 shows the comparison structure for PLA and PLA/Aluminium using SEM.



(a) (b)

Figure 4. Structure comparison using SEM for (a) PLA and (b) PLA/Aluminium

Based on the SEM analysis, the consistency of the printed layer thickness of PLA and PLA/Aluminium composite varies. Figure 4(a) shows that the printed layer thickness of PLA was very consistent for every layer between 91.005 µm to 91.6 µm. Meanwhile, the printed layer for PLA/Aluminium was less consistent with thickness values in the range of 86.000 µm to 99.005 µm. The inconsistent layer thickness contributes to the low strength of PLA/Aluminium composite compare to the PLA material. Inconsistency of the printed layers can cause weak bonding for the structure which may lead to brittle fracture. It is also evident from Figure 5 that the inconsistent extrusion process of PLA/Aluminium creates porosity to the structure and ultimately affects the overall strength of the printed parts. The presence of aluminum reinforcement fillers in the PLA may cause easy separation between each layer [20].

Thus, analyzing the printing parameters for different materials is essential to achieve the optimum outcome.

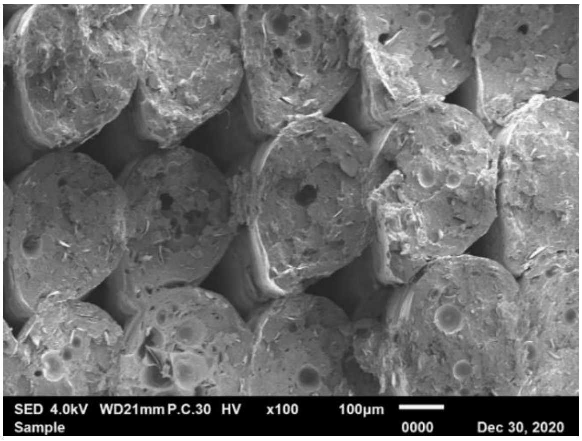


Figure 5. Porous printed structure for PLA/Aluminium material.

ANOVA analysis for PLA and PLA/ Aluminium. The ANOVA analysis for PLA and PLA/Aluminium are tabulated in Table 4 and 5 respectively. The ANOVA analysis for PLA material shows that the number of shells mainly affects the tensile strength value, followed by printing speed and layer thickness. The ANOVA analysis on PLA/Aluminium reveals that increasing the number of shells provides a rigid and strong structure which contributes to the highest tensile strength value.

Table 4. Response table for PLA.

Level	Layer Thickness (mm)	No of Shell	Printing Speed (mm/s)
1	40.13	31.74	36.27
2	35.11	43.23	45.20
3	43.79	44.05	37.55
Delta	8.67	12.32	8.93
Rank	3	1	2

Table 5. Response table for PLA/Aluminium composite

Level	Printing speed (mm/s)	No of shell	Layer thickness (mm)
1	29.37	26.87	28.03
2	30.53	30.40	31.27
3	31.79	34.41	32.38
Delta	2.43	7.54	4.35
Rank	3	1	2

Figure 6 shows that the higher the number of shells the higher the tensile strength value. Number 3 in the graph indicates the highest number of shells which is 7 as mentioned in the previous section in Table 2. The layer thickness can also be tuned to obtain better performance by choosing the lowest layer thickness that contributes to the higher tensile value. Meanwhile, the best printing speed in this study for PLA/Aluminium based on this analysis is 90 mm/s.

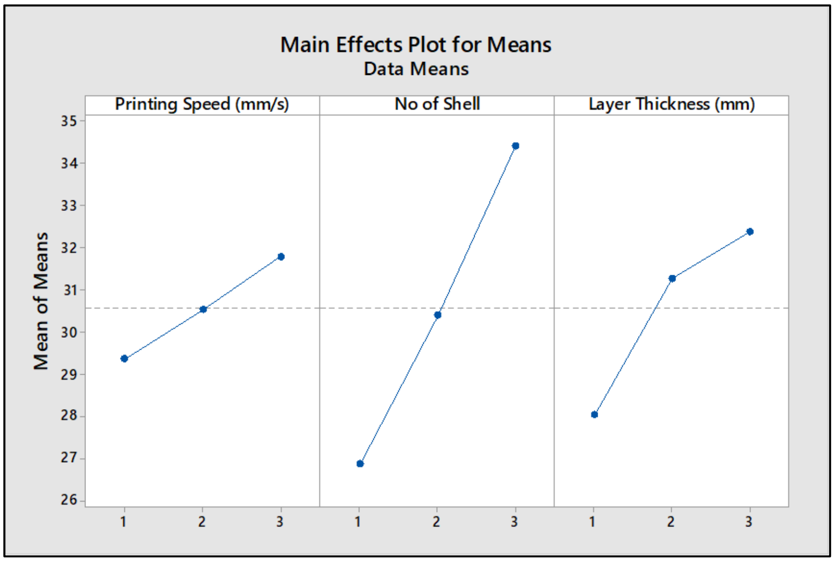


Figure 6. Main effect plot for PLA/Aluminium

From the result, it shows that the PLA material has superior performance compared to the PLA/Aluminium where overall, PLA possess more than 20% higher value of tensile strength compared to PLA/Aluminium. Some of the reasons are due to the extrusion performance which may affect the printed parts. The PLA/Aluminium shows inconsistent layer height on the printed parts and porous structure which may be the cause of lower tensile strength and may lead to brittle fracture. On the other hand, PLA materials show better consistency in the printed layer and provide a strong and rigid structure to hold the force. Another factor that can be considered is the presence of an aluminum compound in the PLA added as reinforcements may causing easy separation between each layer [20]. This finding can be useful to tailor the printed parts for obtaining higher tensile strength for different applications.

Conclusion

This research was carried out to compare the effect of printing parameters on the tensile strength performance of PLA and PLA/Aluminium. The study was done by manipulating three printing parameters which are printing speed (mm/s), the number of shells, and layer thickness (mm). By using Taguchi's DOE, a total of 18 specimens were printed, and a tensile test was performed. Based on the result, the tensile strength value of PLA is approximately 20% higher compared to PLA/Aluminium. The reason is due to the inconsistency of the printed layer of the PLA/Aluminium which led to a weak bond and structure. Based on the ANOVA analysis, the number of shells has the greatest effect on the tensile strength for both materials. It was concluded that the number of shell provides higher tensile strength for the FDM printed PLA and PLA/Aluminium composite.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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