THE EFFECT OF LAYER THICKNESS AND RASTER ANGLES ON TENSILE STRENGTH AND FLEXURAL STRENGTH FOR FUSED DEPOSITION MODELING (FDM) PARTS

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ABSTRACT: Additive manufacturing(AM) technologies using Fused Deposition Modeling (FDM) is one of the most popular method and is widely used for prototyping and production application. However, the quality of parts produced with FDM can be affected by various process parameters used. Therefore, this study aims to examine the effect of and layer thickness and raster angle on mechanical properties of FDM parts. All the test specimens were built by using Folger Tech 3D printer with two materials which are ABS and PLA. ASTM D638 and D790 standard were followed to carry out the tensile test and flexural test to determine the mechanical properties of tensile strength, and flexural strength. The influence of the layer thickness and raster angle on tensile strength and flexural strength is determine using Analysis of variance (ANOVA). The results show that the variables layer thickness and raster angle affect the flexural strength more than these variables affect the tensile strength of the test specimen. Contrary to the common results, the specimen fabricated using PLA material has higher strength compared to ABS material in this study.

KEYWORDS: *Additive Manufacturing; Fused Deposition Modeling; Raster Angle; Layer Thickness; Mechanical Properties*

1.0 INTRODUCTION

Rapid fabrication of physical representations specifically from three dimensional (3D) computer-aided design (CAD) information are made possible with the technology of additive manufacturing (AM). In addition, AM has no need for traditional tooling or special programming. In contrast to the usual manufacturing technology which is usually subtractive, additive manufacturing is a process of amalgamating materials to make physical objects from 3D model computer data [1]. Recently, several low cost and open-source FDM type machines have been developed and sold in the market, which can produce an assortment of thermoplastic prototypes. FDM is one of the broadly used technologies in AM that can quickly create 3D solid object with intricate geometries [2]. The benefits of FDM include simple material change, operation can be done without supervision, low costs, minimized size and low working temperature [3]. In spite of the fact that FDM is fundamentally utilized for prototyping, with gradual improvement in process and material factors, the possibility of application of the process further improvised and now being considered for direct application on real parts. To be utilized as production parts, suitable mechanical properties are required. However, enhancing the mechanical performance of the product regularly comes to the loss of printing speed, affordability and quality. In FDM process, the mechanical properties, surface finish and geometric accuracy achieved are subjected by number of process parameters such as layer thickness, raster angle, build orientation and air gap.

Therefore, proper selection of process parameters has to be done in order to create a product with high quality to fulfil customer requirement. In this research, the effect of layer thickness and raster angle will be explored. These process parameters available on the FDM machine will change the final product’s mechanical properties such as tensile and flexural properties. Besides that, properties such as cost, part quality and building time could also be affected. There are many process parameters available on the AM machine. Almost all the process parameters will affect the performance measures such as mechanical properties, geometrical accuracy, surface roughness, and build time. During the FDM process, there are many parameters need to be considered. It is necessary to identify and understand the definition of each parameter. This is because process parameter will influence the mechanical properties and the quality of the part. Among the important process parameters are described as follows [4]. The location of the process parameters is shown in Figure 1.

i. Build orientation refers to the part incline on the table with respect to X-axis, Y-axis, and Z-axis
ii. Raster angles is the angle which the heading of bead is located relative to the loading of the part. It is a direction with respect to the x-axis on the bottom part layer on the table.
iii. Layer thickness is the height of the layer placed by the nozzle and it depends on the material used and type of nozzle.
iv. The raster width (road width) is the width of the deposition pathway related to nozzle. The range of the width can vary from 0.3 mm to 1 mm

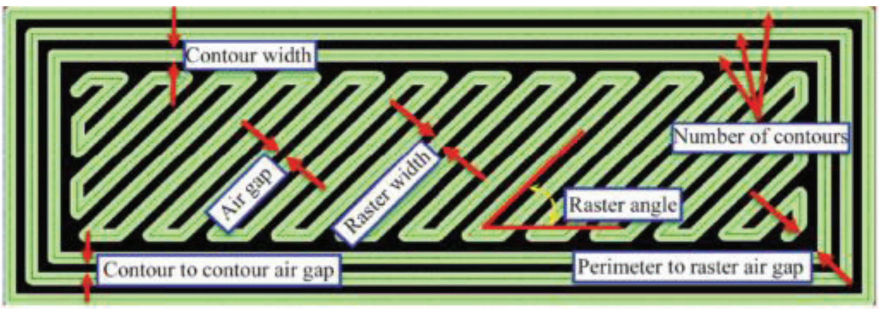


Figure 1: FDM tool path parameters [4]

Lanzotti et al. [5] researched the impact of process parameters on the mechanical properties of PLA parts printed by an open-source 3D printer, where FDM is used to examine the impacts of raster angle, layer thickness, and shell perimeters on the Ultimate Tensile Strength (UTS). The experiment result shows that these three factors had a major effect on UTS, when the raster angle decrease; number of shells increased, and layer thickness increased up to 20 mm, the UTS increased.

Wu et al. [4] studied the impact of raster angle and layer thickness on the mechanical properties of 3D-printed PEEK. Test samples with different raster angles and layer thickness were fabricated using a polyether-ether-ketone (PEEK) 3D printing system and the mechanical properties test such as compressive, tensile and bending strengths were tested. The results show that the average tensile strength of PEEK parts were 108% higher than ABS, and bending strengths were 115% and compressive strength was 114% higher. The test samples fabricated with raster angle of 0°/90° had greater mechanical strength. Therefore, it can be concluded that, the mechanical properties (compressive, tensile and three-point bending) of 3D-printed PEEK test samples were greater than ABS parts. Meanwhile, Lanzotti et al. [6] had studied the parameter impacts of RepRap Open Source 3D Printers Trough a DOE method. Based on the result, it demonstrates that the deposition speed is a critical parameter and the greatest results are acquired using the minimal values of 0.10 mm for layer thickness, 30 mm/s for deposition speed and a 105 flow rate. In Christiyan et al. [7] study, low layer thickness and low printing speed has resulted in maximum flexural and tensile strength, when contrasted with others process parameters test specimen. Tensile and flexural tests are carried out by following ASTM D638 and ASTM D670 standards. Based on result and discussion, it is suggested that flexural strength and tensile is decreasing when the layer thickness increase. Sood et al. [8] have studied the impact of five main process parameters such as part orientation, layer thickness, air gap, raster angle and raster width on mechanical properties of test specimen. Experiment result shows the number of layers in a product relies on the part orientation and layer thickness. Increasing the number of layer thickness improve the strength of the parts. Small raster angle also improves the quality of the parts.

There is no general agreement about the effects of these parameters on mechanical properties. This research studied the influence of raster angle and layer thickness on the tensile strength and flexural strength of FDM test specimens. Finally, the optimum layer thickness and raster angle is identified and presented.

2.0 METHODOLOGY

2.1 Specimens Preparation

The tensile specimens and flexural specimens were printed according to American Society for Testing and Materials (ASTM) standard. The materials utilized as a part of the FDM system can produce tough parts and prototypes. The most popular material used for FDM machine is polylatic acid (PLA) and acrylonitrile-butane-styrene (ABS). The tensile specimens were prepared as dog bone shape with the dimension according to ASTM D638-Standard Test Methods for Tensile Properties of Plastics [9]. This standard is widely used for testing. Due to the test specimen being a rigid plastic, type IV test specimen is chosen. For flexural test, the test specimen was prepared according to ASTM D790. This is a standard test method for flexural properties of reinforced and unreinforced plastics [12]. The dimensions of test specimen for tensile test and flexural test are presented in Figure 2 and Figure 3.

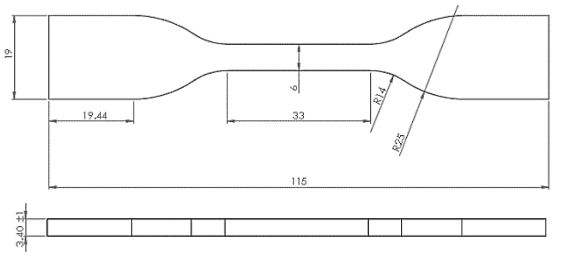


Figure 2: Dimension of dog-bone specimen according to ASTM D638 Type IV [10]

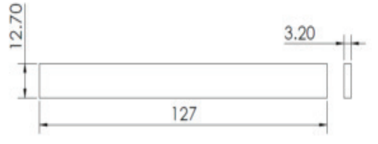


Figure 3: Bending test specimen dimension [9]

To investigate the effect of parameter and mechanical properties, three samples of each combination of parameter were created, with different layer thickness and raster angle, using ABS and PLA material. Other process parameters are kept at their fixed level as mentioned in Table 1. In this research, Design of Experiment (DOE) is used to list out all combination of process parameter layer thickness and raster angle, as shown in Table 2. The geometric models for the test specimen were created in SolidWork and then exported as STL format to be used in the FDM software. The test specimens were built with FolgerTech 3D printer. Sample with three raster angle (30°/60°, 45°/-45°, 0°/90°) and layer thickness (0.2 mm, 0.3 mm, 0.4 mm) were tested for tensile and flexural strength conducted using Ultimate Testing Machine (UTM) [11].

Table 1: Process parameter and their levels

Control Factors	Level	Fixed Factors	Level
Layer Thickness	0.2 mm 0.3 mm 0.4 mm	Build orientation Air gap Fill pattern	Flat Level 1 Rectilinear
Raster Angle	30°/60° 45°/-45° 0°/90°	Fill density Temperature	30% 210°C

Table 2: Combination of parameters

Experiment No.	Factors	
	Raster Angle (degree)	Layer Thickness (mm)
1	0°/90°	0.3
2	30°/60°	0.4
3	0°/90°	0.2
4	30°/60°	0.3
5	30°/60°	0.2
6	45°/-45°	0.4
7	45°/-45°	0.3
8	0°/90°	0.4
9	45°/-45°	0.2

3.0 RESULTS AND DISCUSSION

Tensile and flexural strength of test specimens build with different parameter values of layer thickness and raster angle are analyzed to identify the consequence of these parameter values on the mechanical properties of tensile and flexural strength.

3.1 Results for Tensile Strength

The results of tensile strength for the nine set of specimens are shown in Figure 4. From the experimental results, it can be clearly seen that the strength of PLA specimens is consistently higher the ABS specimen. Normally, ABS is far superior compared to PLA in terms of strength [1, 11]. However, the results obtained were clearly the opposites. One of the main reason could be the environment where the FDM machine, Folgertech was operated. The FDM machine does not have any enclosure thus exposed to a laboratory with temperature as low as 19°C. ABS was well known to produce warping due to have a higher shrinkage factor than PLA. Hence, for the strength of ABS will be clearly depend on the environment it was printed. For PLA specimen, the highest tensile strength was observed at 30°/60° raster angle and 0.4 mm while the highest strength for ABS specimen was observed at 45°/-45° raster angle and 0.4 mm.

In addition, the increase in layer thickness also increases the specimen's strength. A possible reason could be the role of inter-layer and intra-layer bonding [12]. At constant raster angle, the maximum stress increase from 0.2, 0.3 to 0.4 mm. The results were the same with both types of material as well. A solid 0.4 mm layer thickness will have a much higher strength compared to 0.3 mm and 0.2 mm for which both require additional layers to bind each other forming the desired total layer height. When layer thickness increase, the number of layer will decrease [4]. The bonding was imperfect since it was only adhered by mechanical adhesion [12]. Therefore, at raster angle 30°/60° and layer thickness 0.4 mm show the highest tensile strength.

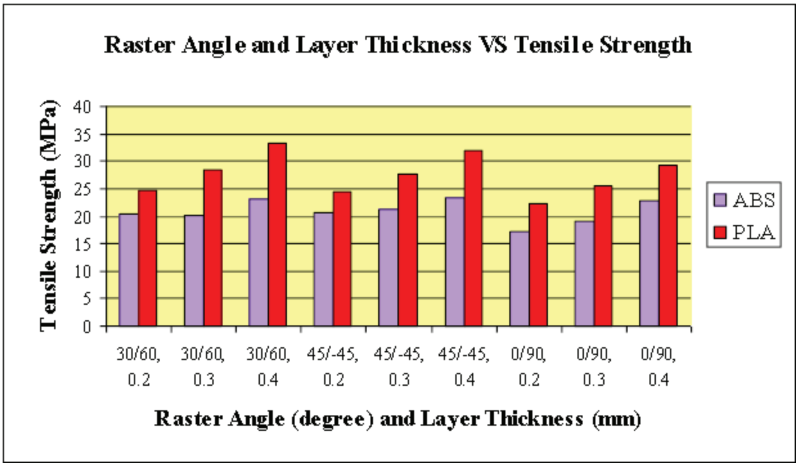


Figure 4: Tensile strength measurements of ABS and PLA specimens with various layer thickness and raster angle

3.2 Results for Flexural Strength

Flexural test for all samples built at different layer thickness and raster angle is shown in Figure 5. From the analysis, the results clearly reveal that the PLA specimen at a constant raster angle of 30°/60°, and 45°/-45°, 0.4 mm layer thickness will have a much higher strength compared to 0.2 mm and 0.3 mm. However, based on the graph, at raster angle 0°/90°, the result shows inconsistent value which the layer thickness 0.4 mm is lower than 0.3 mm. This problem could happen due to an unforeseen error during experimentation such as temperature and humidity. Fragile interlayer bonding caused a reduction in bending strength, and triggered the delamination of welded layers [3, 13]. During the process of additive manufacturing, additional new layer will cover the top of the prior layer.

Then the thermoplastic will solidify and caused shrinkage in the previous layer [3]. In contrast, it was a different case for ABS material. The flexural strength throughout the whole specimens are within 26.48 MPa to 34.31 MPa range. The highest flexural strength was obtained at raster angle 30°/60° and 45°/-45° compare to 0°/90° due to the value of the flexural strength is close to each other. Other than that, the graph also shows that the PLA specimen builds with raster angle of 30°/60° had the greatest flexural strength.

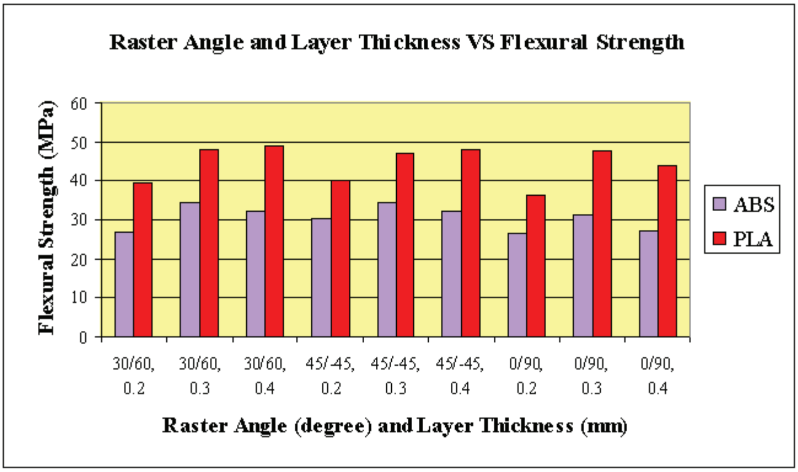


Figure 5: Flexural strength measurements of ABS and PLA specimens with various raster angle and layer thickness

3.3 ANOVA Results

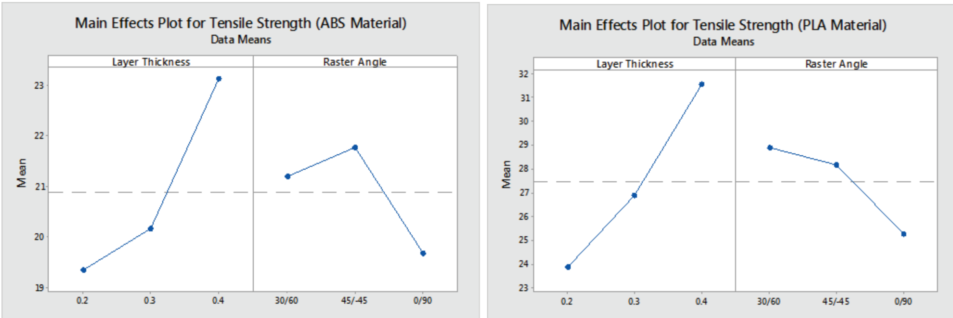
The influence of the FDM process parameter settings is determine with ANOVA. ANOVA results are shown in Tables 3 and 4. The significance level (α) used in the analysis is set to 0.05. If P values are 0.05 or less, it would be considered to have the significant effects to the responses such as tensile strength and flexural strength [14-15]. Figures 5 and 6 show the main effect plot of standardized effects of process parameter on the tensile and flexural strength. There was no statistically significant interaction [16] between the effect of layer thickness on tensile strength, the p-value is greater than 0.05 for ABS specimen $p = 0.416$ and PLA specimen $p = 0.937$ (Table 3). The results show that there was statistically difference in mean tensile strength between various layer thickness $p < 0.001$ and raster angle $p = 0.024$ with ABS specimen. Furthermore, for PLA material, there was statistically difference in mean tensile strength between layer thickness $p < 0.001$ and raster angle $p = 0.002$. This shows that layer thickness and raster angle individually did influence the tensile strength but the effect from the combination of factors is not statistically significant. Table 4 shows the ANOVA result for flexural test. From the results, there was statistically significant interaction between the effect of layer thickness and raster angle on flexural strength with ABS specimen $p = 0.007$ and PLA specimen $p < 0.001$. Besides, there was statistically significant difference in mean flexural strength between various layer thickness $p = 0.001$ and raster angle $p < 0.001$. The results were the same for both types of materials as well. This is because the p-value is less than 0.05, so layer thickness and raster angle individually considered yielding a significant effect on the flexural strength.

Table 3: Two way ANOVA (tensile Strength of ABS and PLA specimen versus layer thickness and raster angle)

	ABS			PLA		
Source	**Adj SS**	**F-Value**	**P-Value**	**Adj SS**	**F-Value**	**P-Value**
Layer Thickness	71.250	15.57	0.000	270.355	34.87	0.000
Raster angle	21.094	4.61	0.024	66.587	8.59	0.002
Layer thickness* Raster angle	9.468	1.03	0.416	3.043	0.20	0.937

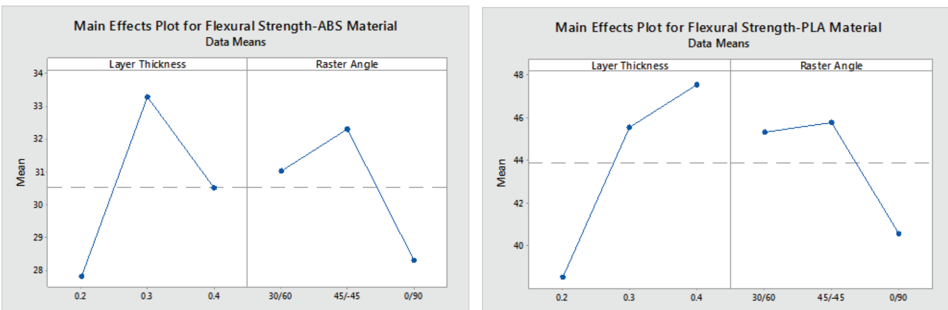
Table 4: Two way ANOVA (flexural strength of ABS and PLA specimen versus layer thickness and raster angle)

	ABS			PLA		
Source	**Adj SS**	**F-Value**	**P-Value**	**Adj SS**	**F-Value**	**P-Value**
Layer Thickness	3.087	10.96	0.001	0.6316	5.52	0.013
Raster angle	13.443	47.76	0.000	9.0864	79.46	0.000
Layer thickness* Raster angle	2.786	4.95	0.007	1.9448	8.50	0.000



(a) (b)

Figure 6: Main effect plot for tensile strength (a) ABS and (b) PLA specimen



(a) (b)

Figure 7: Main effect plot for flexural strength (a) ABS and (b) PLA specimen

4.0 CONCLUSION

In this research, the effect of layer thickness and raster angle on tensile and flexural strengths of parts created with FDM technology are examined for ABS and PLA materials. These are the conclusions from this study:

i. All the experiment results showed that the layer thickness and raster angle have a marked effect on tensile and flexural strength.
ii. Tensile test revealed that 0.4 mm layer thickness has the utmost tensile strength compared to 0.2 mm and 0.3 mm at a constant raster angle. Furthermore, raster angle 30°/60° has the highest tensile strength for PLA material while the highest tensile strength for ABS material are at raster 45°/-45°.

iii. Flexural test showed that the highest value records at layer thickness of 0.4 mm for PLA material and 0.3 mm for ABS material. In addition, there was a similar case for process parameter of raster angle. For ABS material, the highest flexural strength was with the raster angle of 45°/-45° while for PLA material, it was with the raster angle of 30°/60°.

iv. For materials, PLA specimen has the higher value in term of tensile and flexural strength than ABS which is not a norm.

v. The optimum layer thickness was 0.4 mm and 45°/-45° for raster angle to achieve higher mechanical properties.

The optimized set of parameter can be applied and suggested when fabricating a functional part.

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