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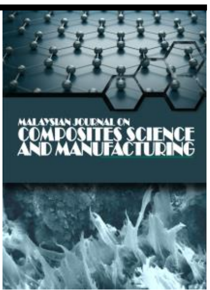
Malaysian Journal on Composites Science
and Manufacturing

Journal homepage:
https://www.akademiabaru.com/submit/index.php/mjcsm/
ISSN: 2716-6945



Effect of Printing Orientation and Layer Thickness on Microstructure and Mechanical Properties of PLA Parts

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ARTICLE INFO

Article history:
Received 13 June 2022
Received in revised form 20 July 2022
Accepted 20 July 2022
Available online 30 July 2022

ABSTRACT

Due to the layer-by-layer printing process, additively manufactured objects frequently display directional dependencies in their structure. It affects the material properties of the fabricated parts concerning various process parameters of the machine. This paper presents the effect of layer thickness and printing orientation on the mechanical properties and microstructure of polylactic acid (PLA)3D printed parts fabricated by Fused Deposition Modeling (FDM). Computer-aided design models of a tensile and compression test specimen were created, conforming to the ASTM: D638 (Type 1 and Type IV) and ASTM D695, respectively. The microstructure was evaluated using a Scanning Electron Microscope (SEM) on the fracture surface during the tensile test and optical microscopy on the compression specimens. The finding shows that a low layer thickness setting contributes to the highest tensile strength in the 0° printing orientation, while a medium and high layer thickness results in a better tensile strength for a 45° and 90° printing orientation. Therefore, printing orientation is more influential than layer thickness in the tensile test. As for the compressive strength, the stress decreases when the layer thickness increases and the low layer thickness setting offers the highest compressive strength at all printing orientations. The microstructure shows more significant interlayer gaps, incomplete filling, and weak bonding on the cross-sectional samples of the fractured tensile surface with lower strength. The 0° printing orientation offers better tensile strength for all layer thicknesses, minimum build time, and good compressive strength compared to other printing orientations.

Keywords:
Layer Thickness, Printing Orientation, Mechanical Properties

1. Introduction

Fused deposition modelling (FDM) is an additive manufacturing (AM) technique that works by a heated nozzle laying down molten material in layers to produce the desired part directly from a computer-aided design (CAD) data file [1]. FDM part is significantly affected by poor and anisotropic mechanical properties [2], which can be improved by proper selection of process parameters [3]. The mechanical properties of FDM parts are significantly affected by printing parameters such as build

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https://doi.org/10.37934/mjcsm.8.1.1123

orientation, layer thickness, and infill density [4]. Employing different levels of layer thickness, for example, affects the build time and influences the mechanical properties of the printed specimen. In addition, different printing orientations can be applied to this manufacturing technique.

On the other hand, the selection of varying printing orientations determines the additional support material used to build the part, resulting in extra build time and directly affecting the part's mechanical properties. It is due to changes in the bonding mechanism of the adjacent layers about the direction of the tensile force. Therefore, this paper aims to present the influence of different printing orientations and layer thickness settings on the mechanical properties and microstructure of PLA samples manufactured with a low-cost 3D printer.

2. Methodology

The material used in this study was Polylactic Acid (PLA). Unlike ABS material, PLA has not been extensively analyzed according to the literature. The study on PLA for the mechanical properties and microstructure is still lacking. Besides, PLA is the most popular FDM 3D printing material in the maker community and is available for most 3D printing supplies vendors. PLA has a relatively low melting point (150°–160°C), which requires less energy to print with than other materials [5]. As a result, PLA has been widely used, and the analysis of its mechanical properties and microstructure is somewhat significant, even though some researchers in [6-8] have investigated the mechanical properties of PLA. However, the studies examined a different combination of process parameters and the effect of PLA colours on its mechanical properties. Therefore, in this present study, different building orientation settings and layer thickness settings were used. Each of these settings was assigned as a high, medium, and low level. The sets were tested to determine their effect and the best level for each, as shown in Table 1. The printing orientation was tested by printing samples in the specific orientations (0°, 45°, 90°) as depicted in Figure 1.

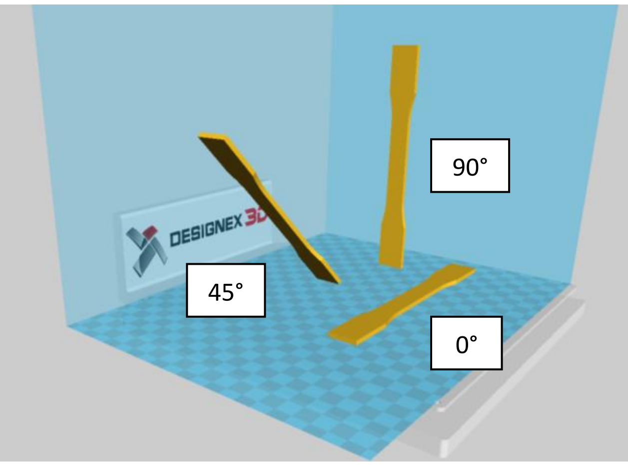


Fig. 1. The considered printing orientation of 0°, 45° and 90°

Table 1 Process parameters and their levels

Parameters	Unit	Levels
Build orientation	°	0, 45, 90
Layer thickness	mm	0.1, 0.3, 0.5

2.1 Tensile Specimen

The tensile specimens were created conforming to ASTM D638 (Type I and Type IV) standards, as shown in Figure 2 and Figure 3, respectively.

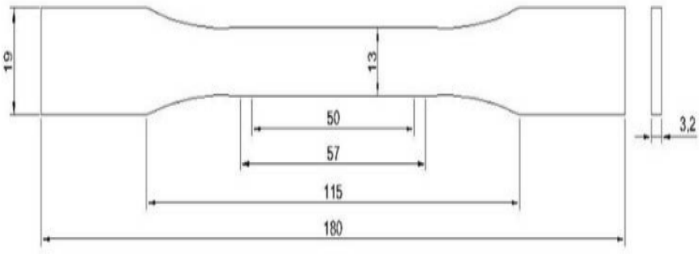


Fig. 2. Tensile specimen according to ASTM D638 (Type I)

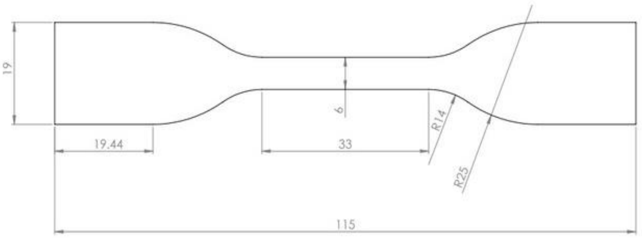


Fig. 3. Tensile specimen according to ASTM D638 (Type IV)

2.2 Compression Specimen

Figure 4 illustrates the compression specimens according to the ASTM D695 standard.

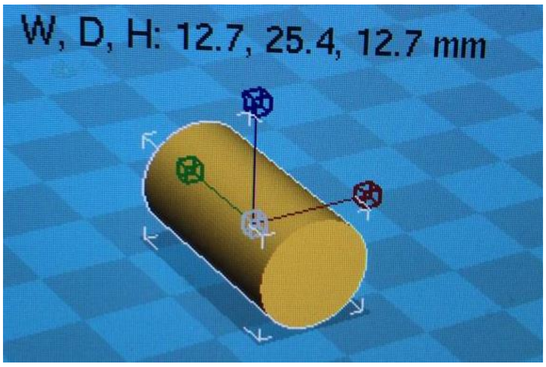


Fig. 4. Compression specimen according to ASTM D695

2.3 General Setting of the FDM Machine

The diameter of the FDM filament was 1.75 mm, while the nozzle size of the machine was 0.4 mm. The bed temperature was controlled to maintain 60°C during each print to ensure that any effect the heated bed may have had on the PLA was consistent throughout all samples. The fill density used was 100%, which defines the amount of plastic used inside the print. A higher infill density means more plastic inside the print, leading to a more robust object. A grid-shaped infill with lines in both diagonal directions on each layer was used for the infill pattern. For the infill line direction, the default infill line of 45° angle was used. At this angle, the X- and Y-motor work together to obtain maximum acceleration and jerk on the layer without losing quality. Details on the other constant process parameters are shown in Table 2. The build time for each setting is indicated in Table 3.

Table 2

The setting of process parameters

Parameters	Value
Shell thickness	0.8 mm
Fill bottom/top thickness	0.4 mm
Fill density	100%
Print speed	60 mm/s
Print temperature	190 °C
Bed temperature	60 °C

Table 3

Build time for tensile specimens (Type I and Type IV)

Setting	Build Time (Type I)	Build Time (Type IV)
0.1, 0	1 hr. 45 min	1 hr. 23 mins
0.1, 45	6 hrs. 17 mins	3 hrs. 28 mins
0.1, 90	5 hrs. 14 mins	3 hrs. 23 mins
0.3, 0	1 hr.	40 mins
0.3, 45	2 hrs. 22 mins	1 hr. 16 mins
0.3, 90	1 hr. 46 mins	1 hr. 9 mins
0.5, 0	48 mins	32 mins
0.5, 45	1 hr. 33 mins	50 mins
0.5, 90	1 hr. 5 mins	43 mins.

2.4 General Setting for the Tensile and Compression Test

In this study, 18 printed tensile samples for each setting combination were subjected to tensile testing consistent with ASTM D638 (Type I) and ASTM D638 (Type IV) standards. The rigid specimens were tested for tensile strength on a SHIMADZU Universal Tensile Testing machine with a 20 kN load cell for load measurement. The test was run at a head travel speed of 5mm/min [9] and was used for the extension measurement. As for the compression test, the travel speed of 1.27mm/min [10] was used.

3. Results

3.1 Tensile Test

Tables 4 and 5 show the tensile test results for ASTM D638 (Type I and Type IV), respectively. According to Torres et al. [8], printing orientation is the main factor that affects the strength of the PLA-printed parts, while layer thickness is the second most influential factor. In this study, the printing orientation of 0° recorded the highest stress value for all layer thicknesses, indicating a higher maximum force required to break the specimen than the printing orientation of 45° and 90° for both Type I and Type IV specimens, as shown in Figure 5. The layer thickness among all printing orientations, on the other hand, reflects a slightly random pattern, where in 0° and 45° printing orientations, a gradual decrease of the stress was observed with the increase of layer thickness for 0.1 mm and 0.3 mm for Type I specimens. However, 0.5 mm layer thickness indicates the highest stress for 90 printing orientation, contradicting to the initial finding and similar to the finding from Chacón et al. [11] which indicated that the tensile strength increased as the layer thickness increased. On the other hand, 0.3 mm layer thickness indicates the most increased stress in 90° printing orientation for the Type IV specimens. The findings show that the 90° printing orientation is better for the medium and high setting of layer thicknesses. In 90° orientation, the layering position of each layer is built parallel to to the tensile load, as illustrated in Figure 10. The adhesion mechanism between layers is easily pulled out with less force, and the larger layer thickness require additional force to break the layer bonding compared to the lower layer thickness. Therefore, this might be the reason for this distinct pattern. Thus, in terms of the layer thickness, a layer thickness of 0.1 mm only offers the best tensile strength at the 0° printing orientation, as with the 45° and 90°, the medium and high layer thickness (0.3, 0.5 mm) show a better strength. Therefore, only at the printing orientation of 0° can the expected tensile strength be predicted accurately according to the layer thicknesses.

Table 4
Tensile result for ASTM D638 (Type I) specimens

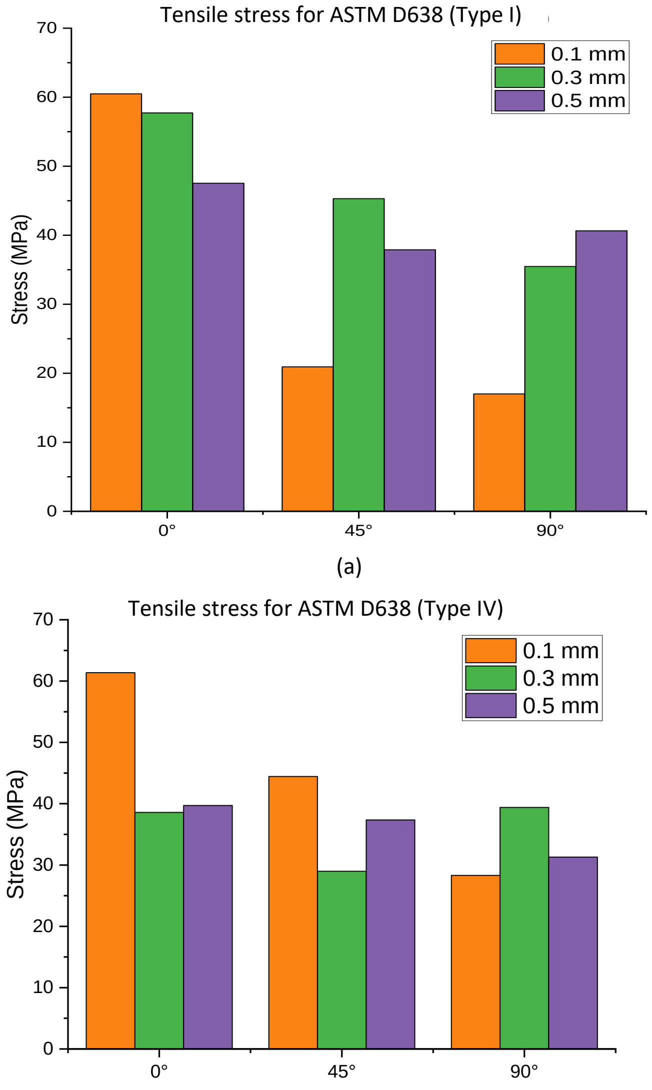
	0.1 mm		0.3 mm		0.5 mm	
	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)
0°	60.4839	2.95572	57.7278	3.25789	47.5444	3.39704
45°	20.9222	1.34263	45.2948	3.85207	37.8883	5.15569
90°	17.0090	0.56516	35.4742	2.32598	40.6401	2.81657

Table 5
Tensile result for ASTM D638 (Type IV) specimens

	0.1 mm		0.3 mm		0.5 mm	
	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)
0°	61.3692	3.01910	38.5867	2.59981	39.7151	2.67804
45°	44.4375	4.92158	28.9891	2.98064	37.3489	3.54215
90°	28.3012	1.37694	39.4034	2.59731	31.2885	2.59475

Table 6
Compression test result for specimens of ASTM D695

	0.1 mm		0.3 mm		0.5 mm	
	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)
0°	89.8327	9.21019	49.6738	49.3065	13.6539	5.25153
45°	88.6488	50.1946	73.1006	49.5060	25.7417	49.4330
90°	88.0533	49.4296	47.5391	49.4923	37.5608	49.5831



(a)

(b)

Fig. 5. Tensile stress for all layer thicknesses at all printing orientations: (a) (Type I), (b) Type IV

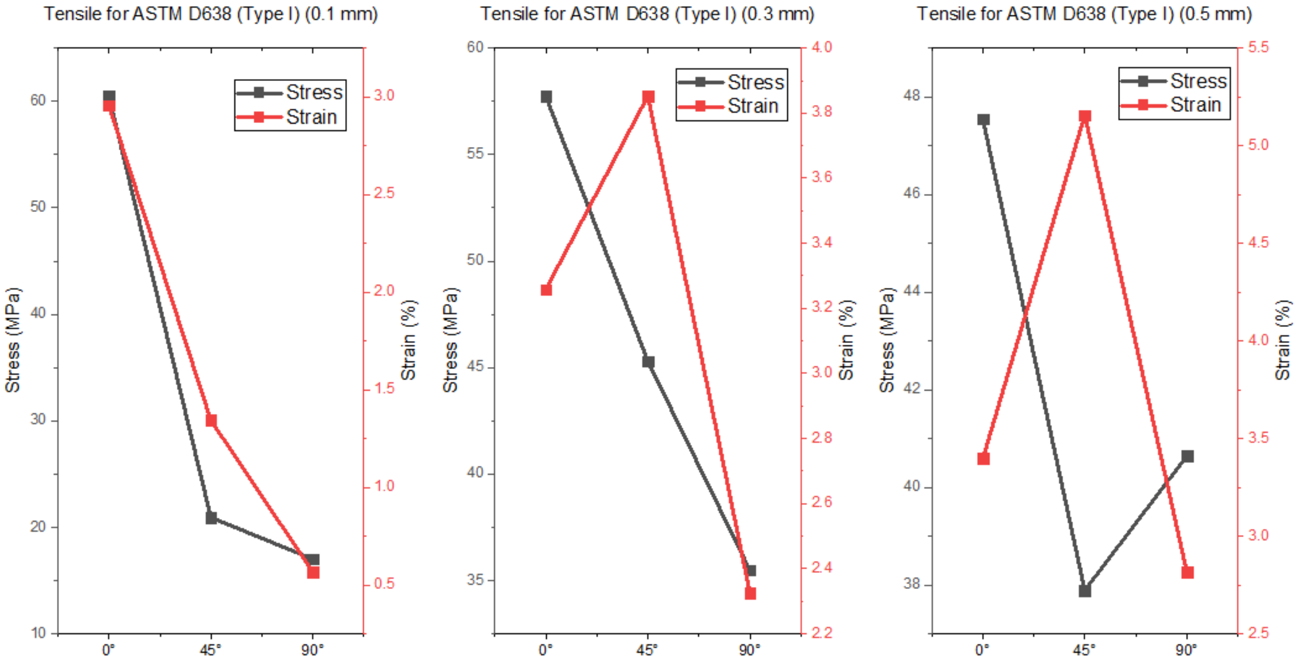


Fig. 6. Stress and strain pattern for Type (I) (a) 0.1mm, (b) 0.3 mm, and (c) 0.5 mm

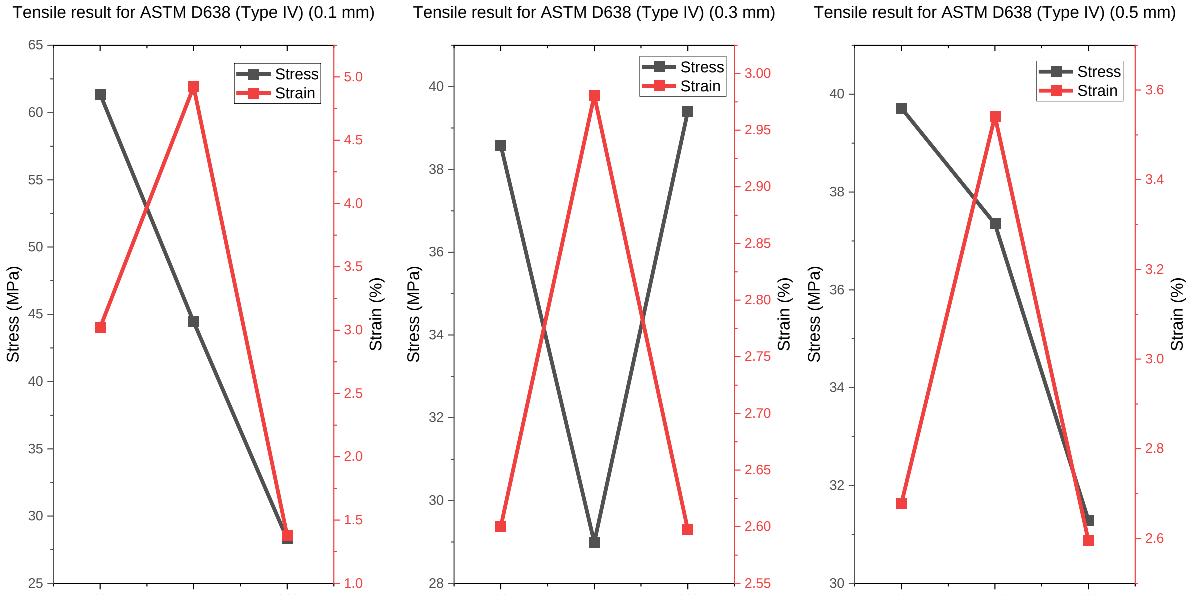
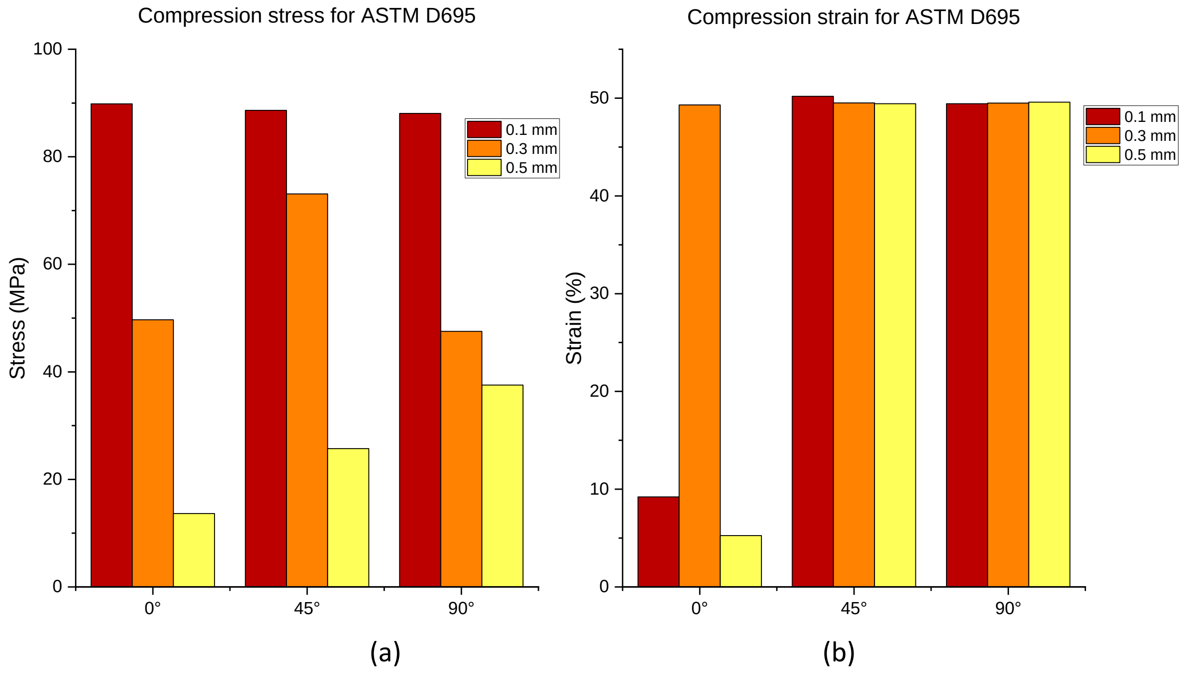


Fig. 7. Stress and strain pattern for Type (IV) (a) 0.1mm, (b) 0.3 mm, and (c) 0.5 mm

Figures 6-7 illustrate the stress and strain pattern for each layer thickness setting at different printing orientations for Type I and Type IV, respectively. In Type I and Type IV specimens, the patterns show ununiform relationships. Most of the patterns exhibit a disproportionate relationship between stress and strain, which means at the lowest tensile stress, the elongation of the material is high, indicating the highest strain value. The strain value is high for the printing orientation of 45°, indicating that the elongation of the specimen is high before rupture.

3.2 Results of the Compression Test

Table 6 shows the results of the compression test for all settings. According to the results, higher compression strengths were recorded for the layer thickness of 0.1 mm at all printing orientations (0°, 45°, 90°) compared to the layer thickness of 0.3 mm and 0.5 mm. The maximum compression strength was obtained for the printing orientation of 0° and the layer thickness of 0.1 mm (Figure 8a). However, the stress values for the medium and high setting of layer thicknesses (0.3 and 0.5 mm) indicate the increase of stress values in printing orientations of 45° and 90° compared to printing orientations of 0°. On the other hand, the compression stress values for 0.1 mm layer thickness show no significant changes in compressive stress at all printing orientations. However, the medium and high layer thickness setting (0.3, 0.5 mm) results in higher compressive stress at 45° and 90° printing orientations. To conclude, a similar reduction pattern was observed for all printing orientations, indicating that the compressive strength decreases when the layer thickness increases. The compressive strain, however, is higher for all layer thicknesses in printing orientations of 45° and 90° (Figure 8b).



(a) (b)

Fig. 8. (a) Compressive stress and (b) compressive strain

Figure 9 depicts the compressive stress and strain pattern for each layer thickness at different printing orientations. For layer thickness of 0.1 mm, the stress is disproportionate to the strain, where the highest stress resulted in the lowest strain value. On the other hand, a proportional relationship is observed for the layer thickness of 0.3 mm and 0.5 mm, respectively.

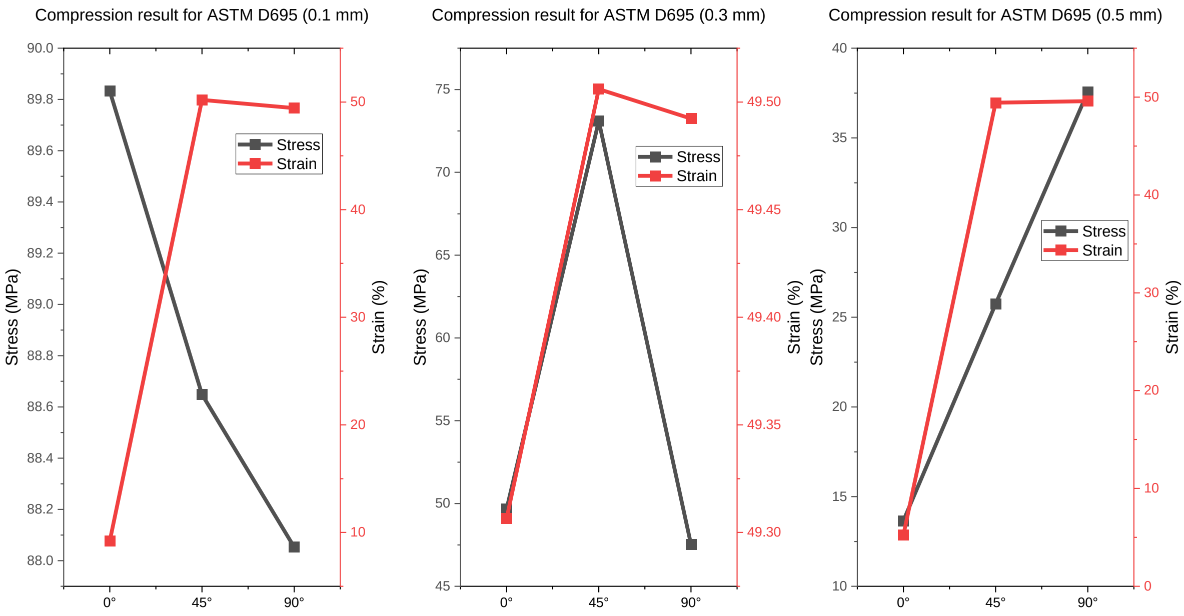


Fig. 9. Compressive stress and strain pattern (a) 0.1mm, (b) 0.3 mm, and (c) 0.5 mm

3.3 Analysis of the Tensile Result

In general, printing orientation 0° needed more tensile strength for all layer thickness, while printing orientation 90° required less tensile strength. Upright orientation (90°) showed the lowest mechanical properties, and the mechanical properties increase as layer thickness increases for this printing orientation [11]. Theoretically, a lower layer thickness value is good for tensile strength because of the higher bonding area between the layers. This could be referred to as the layer thickness of 0.1 mm. However, different printing orientations influenced the mechanical properties and contradicted this statement. It was demonstrated by the printing orientation of 90° (upright), where the mechanical properties increased as the layer thickness increased. Figure 10 illustrates the tensile test for the printing orientation of 0° and 90°, which might explain why the 90° orientation required less tensile strength than the 0° printing orientation.

On the other hand, the polymer filament type and quality have also been observed to be an essential factor in printing, whether in ABS or PLA [6]. Wittbrodt and Pearce [7] showed a strong relationship between percent crystallinity and the extruder temperature. Since the used FDM machine in this study was a low-cost 3D printer, a few technical problems were encountered while printing all specimens. The most challenging setting to be printed was the printing orientation of 45°. As a result, the variation in the tensile test results for this setting was obtained.

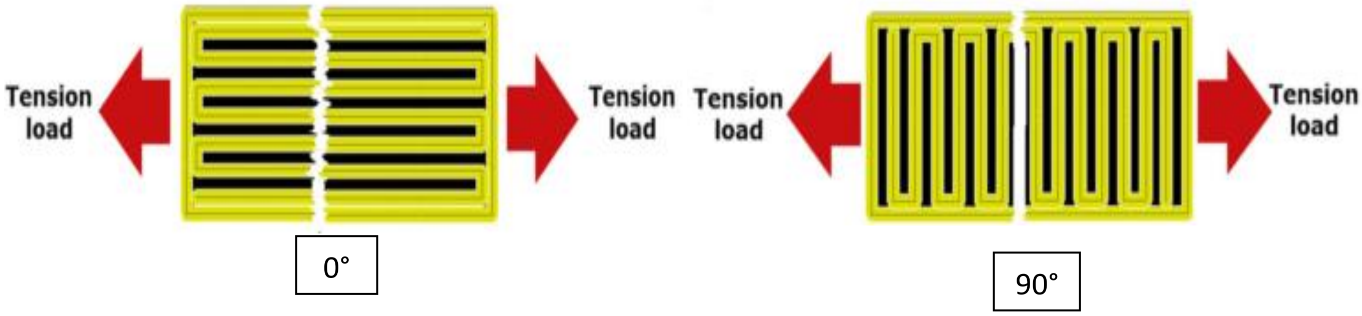


Fig. 10. Tensile loading on different printing orientations (0° and 90°) [12]

3.4 Analysis of the Compression Result

Figure 11-13 show the optical microscopy images for all settings. As previously discussed, a layer thickness of 0.1 mm showed the highest compressive strength. This could be observed in Figure 11, where the bonding between each layer was still attached. On the other hand, the layer thickness of 0.5 mm showed the lowest compressive strength, starting with 0°, 45°, and 90°, respectively. Figure 13 illustrates the final part after the compressive test for this layer thickness setting. According to this, the 0° printing orientation indicated the ruptured layer bonding, similar to the 45° and 90° printing orientation. In addition, the final compressive stress result for the layer thickness of 0.3 mm indicated that the printing orientation of 45° required the highest compressive strength. Figure 12 shows the layer bonding for this specimen is still in contact, contrary to the 0° printing orientation.

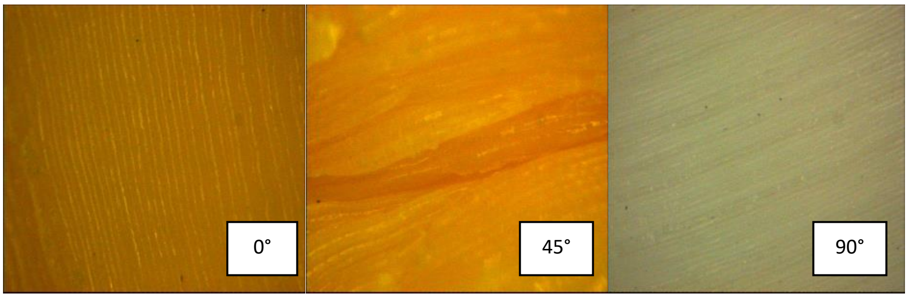


Fig. 11. Optical microscopy result of 0.1 mm layer thickness at 20x magnifications

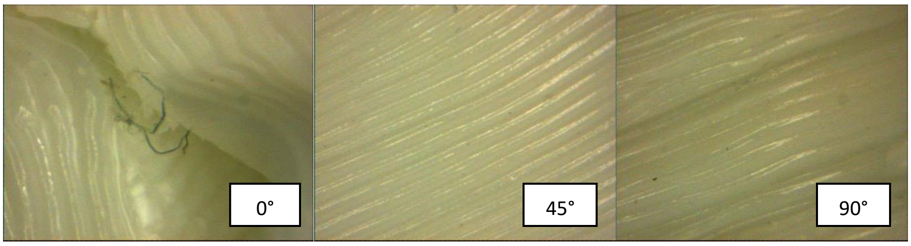


Fig. 12. Optical microscopy result of 0.3 mm layer thickness at 40x magnifications

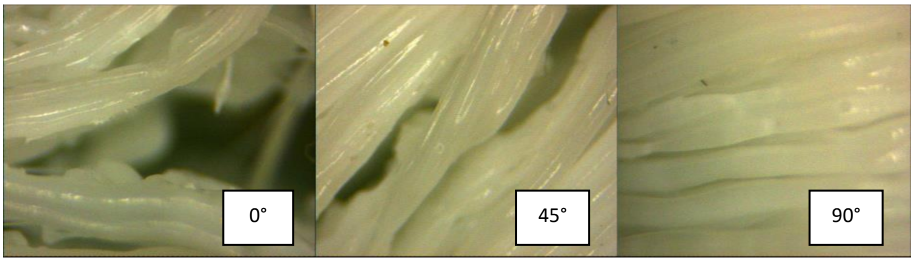


Fig. 13. Optical microscopy result of 0.5 mm layer thickness at 60x magnifications

3.5 Analysis of the microstructure

The fractured surface of the tensile test was subjected to microstructure analysis to see the layered printing effect of the specimen with different printing orientations and the layer thickness setting. Scanning electron microscopy was used to characterize the morphological characteristics of the blend [13]. Poor adhesion was observed at the interface between blend components. Initially, the sputter-coated specimen was executed to eliminate the charging effects during the SEM analysis. Additive manufactured parts contain complex mesostructures that result in directionally-dependent mechanical properties that have yet to be fully characterized [14]. Figure 14 shows SEM images with details of the fractured surfaces for Type I specimens. A comparison of the 0.5 mm layer thickness (Figure 14a) and 0.3 mm layer thickness (Figure 14b) illustrates that larger voids between adjacent layers exist in 0.5 mm, causing a slightly lower tensile strength. In the 0° orientation, the molecules tend to align themselves parallel to the stress axis, and this would produce the most substantial direction for the layers [15]. Likewise, weak interlayer bonding or interlayer porosity in any orientation can lead to layer delamination along that orientation during loading. Examination of the fracture surfaces revealed fracture paths controlled by either weak interlayer bonding or interlayer porosity, as shown in Figure 14c. On the other hand, humidity can also influence the mechanical properties of 3D printed parts due to the water's existence, altering the polymer chain's bonding, resulting in a lower mechanical strength [16].

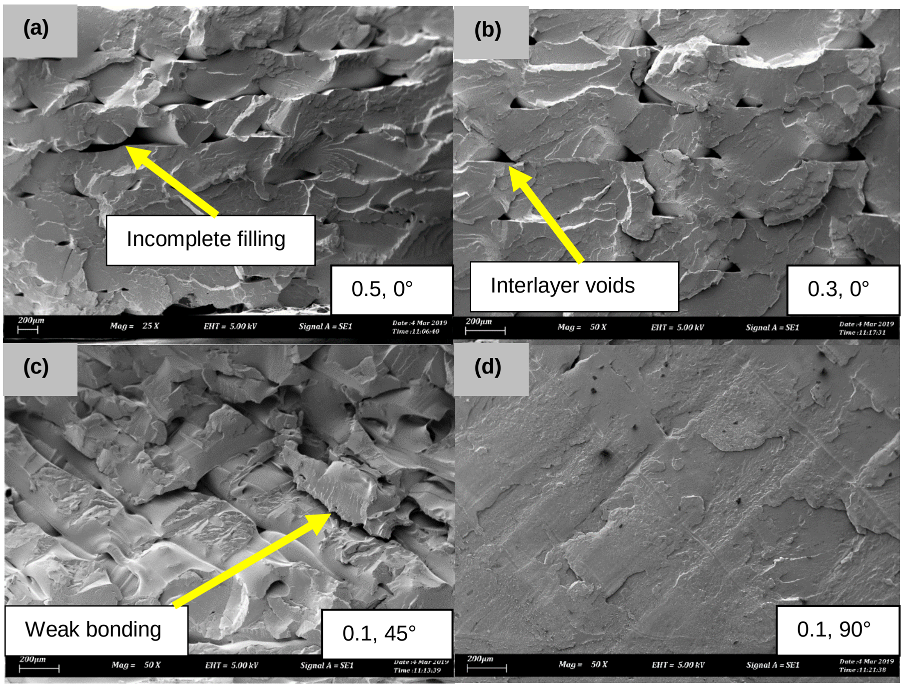


Fig. 14. SEM images of the fractured tensile surfaces at (a) 25x and (b-d) 50x magnifications

4. Conclusions

To conclude, printing orientation is the main influential factor that affects the strength of PLA printed parts, followed by layer thickness as the second factor. The results from this study clearly showed that printing orientation significantly affected the mechanical properties. Tensile data of PLA specimens with different orientations indicated that tensile strengths were the highest in 0° printing orientation for all layer thicknesses. In this case, the molecules tend to align themselves parallel to the stress axis, and this would produce the most substantial direction for the layers. The fracture path of the tensile samples depended on the layer orientation, where delamination occurred along with the layer interface. This was caused by weak interlayer bonding and interlayer porosity. In addition, upright orientation (90°) showed the lowest mechanical properties, and the tensile strength increased when the layer thickness increased. For the 90° orientation, the samples were pulled parallel to the layer deposition direction, and the load was perpendicular to their fibres, resulting in inter-layer fusion bond failure. As for the compressive strength, 0.1 mm layer thickness shows the highest strength at all printing orientations. The compressive strength decreases with the increase of layer thickness. However, the compressive strength of 0.3 and 0.5 mm layer thickness increases in printing orientation of 45° and 90°. The low layer thickness is preferential due to much smaller gaps. The recommended setting to achieve the highest tensile and compressive strength is a 0° printing orientation (flat) with a layer thickness of 0.1 mm. A medium and high-level layer thickness is recommended at 45° and 90° printing orientations.

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