



## THE EFFECT OF ORIENTATION AND LAYER THICKNESS ON THE TENSILE STRENGTH OF THE 3D PRINTED SPECIMENS

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### تأثير الاتجاه وسمك الطبقة على مقاومة الشد لعينات الطباعة ثلاثية الأبعاد

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#### الملخص

حظيت تقنية التصنيع بالإضافة (AM)، والمعروفة باسم الطباعة ثلاثية الأبعاد، باهتمام كبير من المصنعين نظرًا لقدرتها على تصنيع أشكال معقدة، تقليل الوقت والتكلفة، فضلاً عن تحسين الخواص الميكانيكية. لذا يهدف هذا البحث إلى دراسة تأثير كل من سمك الطبقة واتجاه العينة على خصائص المواد لعينات (PLA) المصنعة بالطباعة ثلاثية الأبعاد باستخدام تقنية الترسيب المنصهر (FDM). حيث أجريت الطباعة في ثلاث اتجاهات  $0^\circ$ ،  $45^\circ$ ،  $90^\circ$ ، وسمك للطبقة الواحدة 0.1، 0.2، 0.3 مم بمساعدة SolidWorks في تصميم العينات وإعدادها وفقاً لـ ASTM D638. أظهرت النتائج أن التغييرات في آلية تصنيع العينات بالطباعة ثلاثية الأبعاد يمكن أن تحسن الخواص الميكانيكية للمادة، خصوصاً مقاومة الشد القصوى والانفعال. حيث لوحظ أن اتجاه الطباعة في نفس اتجاه التحميل ( $0^\circ$ ) أظهر أقصى مقاومة شد مقارنة باتجاهات الطباعة الأخرى. بينما التغيير في سمك الطبقة له تأثير ضئيل على قوة الشد. ومع ذلك، فإن لزيادة سمك الطبقة تأثير على زيادة الانفعال. يمكن أن تساعد هذه النتائج المصممين في اختيار الاتجاه المناسب لطباعة العينة وسمك الطبقة المناسب لتحسين الخواص الميكانيكية.

**الكلمات المفتاحية:** التصنيع بالإضافة، الطباعة ثلاثية الأبعاد، نمذجة الترسيب المنصهر، بوليمر حمض البوليلاكتيك.

#### ABSTRACT

Additive manufacturing (AM) known as 3D printing has attracted significant interest from manufacturers due to its ability to fabricate complex shapes, reduce time and cost, as well as to improve the mechanical properties. This research aims to investigate the interaction effect of layer thickness and specimen orientations on the material properties of the 3D-PLA (polylactic acid) printed specimens using fused deposition modelling (FDM). Three orientations  $0^\circ$ ,  $45^\circ$  and  $90^\circ$  and three thicknesses 0.1, 0.2, and 0.3mm were considered. The specimens were designed using SolidWorks and prepared according to ASTM D638. The results confirmed that the change in the mechanism of fabrication of the 3D printing specimens can improve the mechanical properties of the material,



particularly the tensile strength and strain. It was observed that printing orientation of  $0^\circ$  provides maximum tensile strength, while changes in layer thickness have an insignificant effect on it. However, the increase in layer thickness has an important effect on the total strain which increases as the layer thickness increases. These results can assist designers in selecting the proper orientation of printing and appropriate layer thickness to improve mechanical properties.

**KEYWORDS:** Additive manufacturing, 3D printing, fused deposition modelling, polylactic acid polymer.

## INTRODUCTION

Additive manufacturing (AM) technology has been widely adopted in modern industry to produce prototypes and end-use products. The AM has advantages over traditional manufacturing processes in terms of its ability to optimize mechanical properties and fabricate complex parts [1]. The technology has been used in several engineering and medical applications including automotive, aerospace, and biomedical engineering. Its fundamentals involve depositing consecutive layers based on a digital design which eliminates the need for expensive tools and reduces fabrication costs. Several 3D printing mechanisms are available, such as photopolymer inkjet printing (PIP), aerosol jetting (AJ), direct ink writing (DIW), and fused deposition modeling (FDM) [2]. Among these, FDM is the most widely used method due to its simplicity, material flexibility, and low cost [1], [3]. The technique can also be used to improve mechanical properties by controlling printing parameters such as infill density, raster pattern, layer thickness, and build orientation [4], [5], [6], [7]. It was shown that the infill pattern and density play a substantial role to enhance tensile strength and elastic modulus of 3D printed specimens [8]. Tensile tests revealed a significant influence of the infill density on the mechanical behavior of 3D printed parts [9]. Reference [9] observed that the strength and stiffness increase as the infill density increases. Similar observations were reported in [10] where a higher yield strength was associated with specimens printed with a higher infill density.

Other parameters besides infill density, such as raster angle and orientation play a substantial role. A review in [11] concluded that raster angle significantly improves mechanical properties, noting that a raster angle of  $0^\circ$  yields better mechanical properties compared to  $45^\circ$  and  $90^\circ$ . They observed that the breaking force increases as the number of layers increases. Reference [12] investigated the influences of the raster angle and number of layers on modulus of elasticity and ultimate tensile strength. They showed that the tensile strength and elastic modulus were maximum for the raster angle of  $0^\circ$ , and both increase as the number of layers increases up to 12 layers. However, further increase in number of layers has an insignificant effect. Reference [13] showed that printing orientation significantly affects tensile strength, while the strain remains unaffected. This trend is consistent with the results in [14] and [15], which showed the tensile strength decreases as orientation increases from  $0^\circ$  to  $90^\circ$ , with samples printed at  $0^\circ$  exhibited the highest strength.

Extensive research in the literature focuses independently on the effects of orientation and layer thickness on tensile strength. However, there is a lack of research on the combined effect of these two parameters on tensile strength, total strain, and failure characteristics. It also remains unclear whether the influence of layer thickness is consistent across all orientations. Therefore, this research aims to investigate the

interaction effect of layer thickness and specimen orientations on the material properties of 3D-PLA printed specimens using fused deposition modelling FDM.

### MATERIALS AND SPECIMEN DESIGN

A polylactic acid (PLA) filament (eSUN) with a diameter of 1.75 mm was used as the material of interest. A set of 54 standard tensile specimens of type I, according to ASTM D638 shown in Figure (1) was modeled in SolidWorks and exported in stereolithography (STL) format for slicing using a PrusaSlicer.

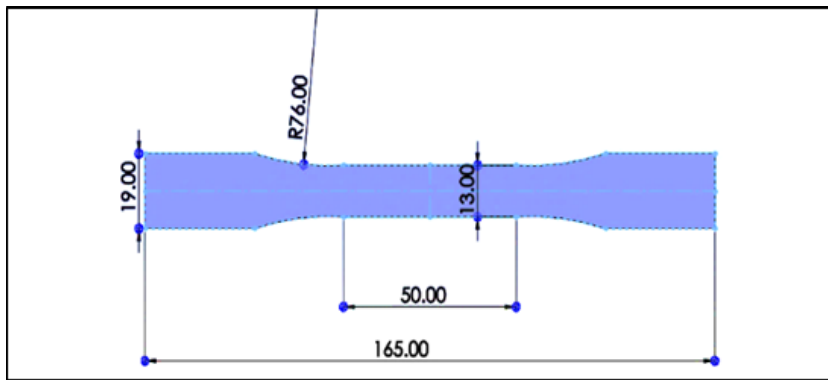
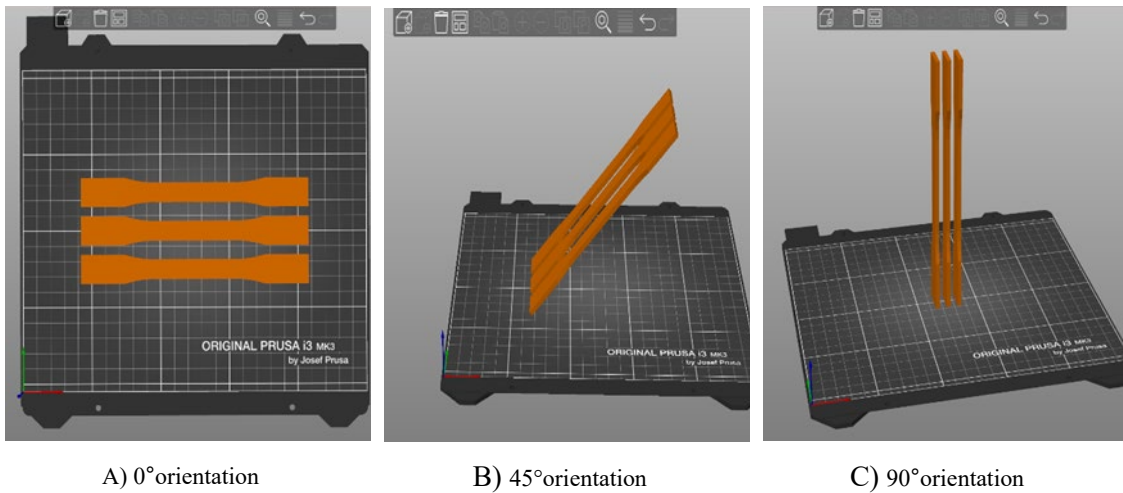


Figure 1: Specimen geometry and dimensions in mm.

Table (1) illustrates the design of the experiment where two parameters were considered for the investigation, namely, layer thickness and specimen orientation. The layer thicknesses of 0.1 mm, 0.2 mm, and 0.3 mm were used to obtain the full specimen thickness of 7 mm. Each layer thickness was tested for three different orientations  $0^\circ$ ,  $45^\circ$  and  $90^\circ$  measured from the horizontal axis. Each group included six specimens printed at each orientation ( $0^\circ$ ,  $45^\circ$ , and  $90^\circ$ ), for a total of 18 specimens per thickness level. Figure (2) shows the orientation of printing of the specimens. In case (A) where printing is at an orientation of  $0^\circ$  the printed layers are parallel to the direction of tension, in case (B) the printed layers are inclined at an angle of  $45^\circ$  from the direction of tension, while in case (C) the printed layers are perpendicular to the direction of tension that is  $90^\circ$ .

Table 1: Layer thickness and orientation.

Number of specimens	Layer thickness (mm)	Orientation (deg)
6	0.1	$0^\circ$
6	0.1	$45^\circ$
6	0.1	$90^\circ$
6	0.2	$0^\circ$
6	0.2	$45^\circ$
6	0.2	$90^\circ$
6	0.3	$0^\circ$
6	0.3	$45^\circ$
6	0.3	$90^\circ$
Total=54		



**Figure 2: Considered orientations for the 3D printed specimens.**

## PRINTING PROCEDURE

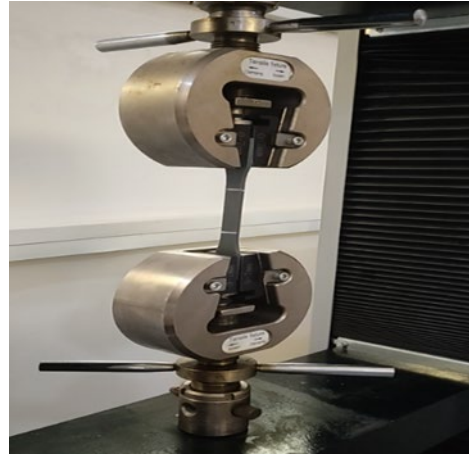
Specimens were printed using Prusa i3 MK3S FDM 3D printer with infill density of 75% and linear infill pattern. Table (2) shows the set-up parameters that were considered constant during the printing for all specimens. The values of the parameters adopted in this work are widely used and available in the literature.

**Table 2: Set-up parameters.**

Parameter	Value	Unit
Nozzle diameter	0.4	mm
Extruder temperature	210	°C
Heated bed temperature	60	°C
Print speed of the first layer	30	mm/s
Print speed of outline	40	mm/s
Print speed	90	mm/s
Travel speed	150	mm/s

## TENSILE TESTING

Tensile tests were conducted at room temperature under ambient conditions using the HST Group mechanical testing machine (WDS-50) shown in Figure (3). The test speed of 5 mm/min was chosen according to ASTM D638 Type I [16] and based on the specifications of the material being tested.



**Figure 3: Tensile testing machine at the Advanced Center for Welding, Tajoura, Libya.**

## RESULTS AND DISCUSSION

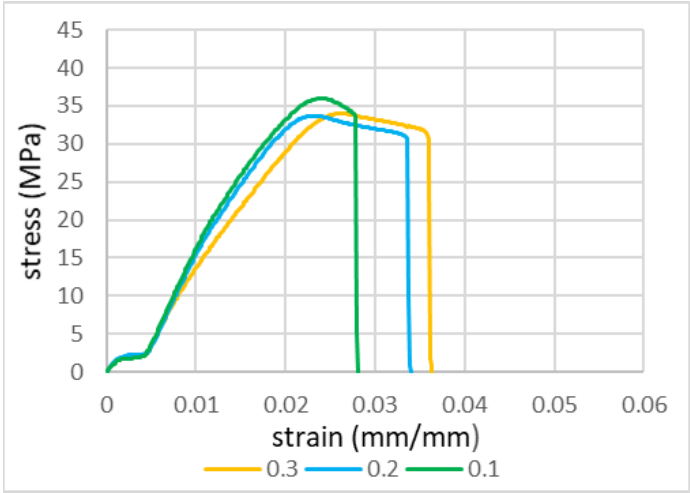
The tested specimens were accepted when the final fracture occurred within the narrow area as shown in Figure (4).



**Figure 4: The specimens after the test.**

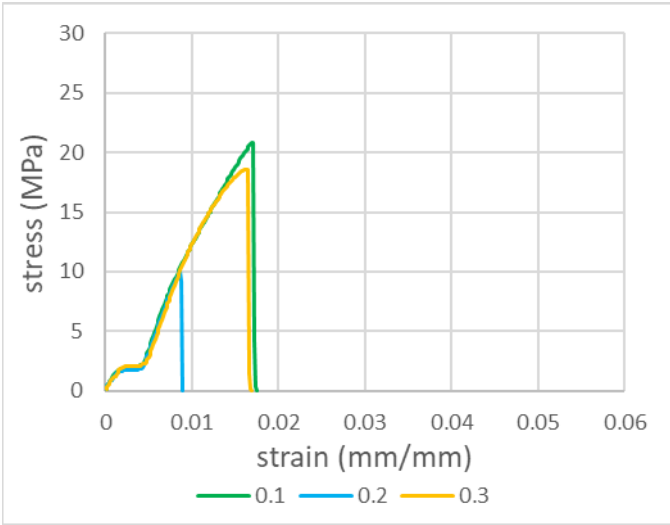
The stress-strain curves for  $0^\circ$  orientation with layer thicknesses of 0.1, 0.2 and 0.3 mm are shown in Figure (5). The figure illustrated that all layer thicknesses exhibited a

relatively brittle behavior accompanied by a considerable elongation before fracture. It can be seen that the strain increases as layer thickness increases, particularly for 0.3 mm. while stress remains almost consistent across all considered layer thicknesses around 35 MPa. These results are in agreement with [14] where the PLA specimens exhibited a tensile strength of 35.16 MPa at 0° orientation. A marginal difference in results was observed in [15] where the maximum stress was 28.7 MPa for 0° orientation.

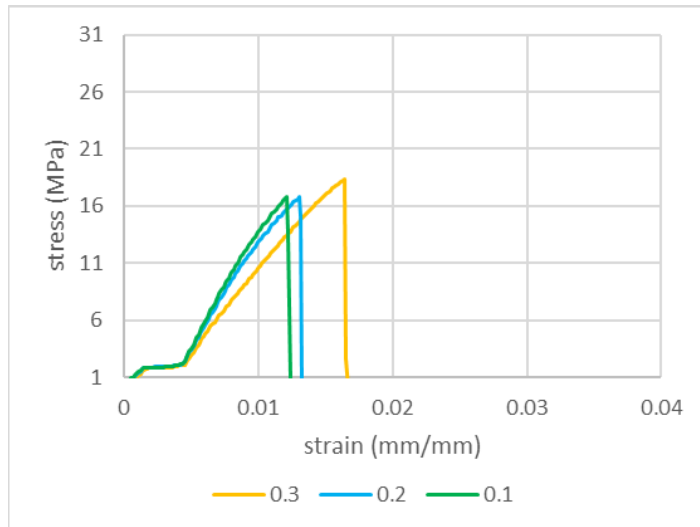


**Figure 5: Stress-Strain curve for 0° specimens.**

Different profile was observed for specimens printed with an orientation of 45° as shown in Figure (6), where a brittle behavior was maintained. The stress and strain values are smaller than those obtained for 0° orientation. A sudden fracture occurred for all specimens after reaching the maximum stress value. For specimens orientated at 90° in Figure (7), a brittle behavior was also sustained regardless of thickness. The obtained maximum stress of 16.4 MPa is consistent with the results in [14] and [15] who reported the highest tensile strength of 17 MPa at 90° orientation.

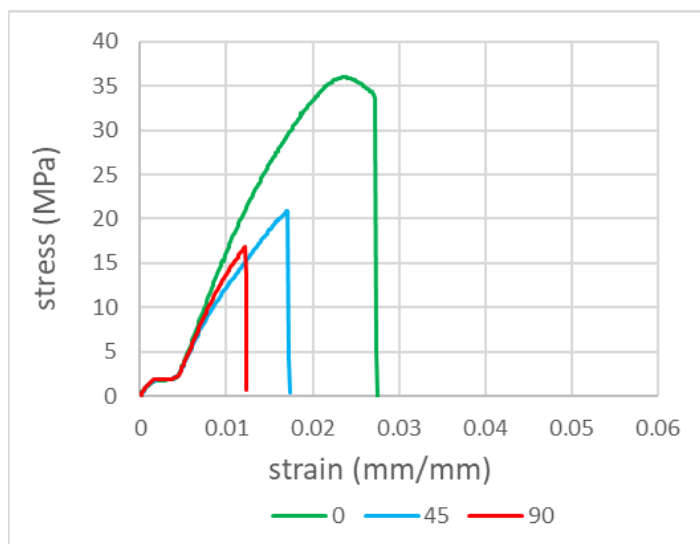


**Figure 6: Stress-Strain curve for 45° specimens.**



**Figure 7: Stress-Strain curve for 90° specimens.**

Figure (8) shows the largest stress and strain for 0.1 mm layer thickness were associated with orientation of 0°. It also shows that the material's behavior is clearly different where 0° specimens revealed a brittle behavior associated with a considerable elongation. This is due to the applied load is parallel to the direction of filling along the longitudinal axis of the specimen. In contrast, 45° and 90° orientations exhibited completely brittle behavior, with 90° orientation had the smallest stress and strain. This is due to the printing direction, which imposes layers bonded perpendicular to the tensile load. These findings are in agreement with the results in [17] which reported that flat orientations exhibited the highest values of maximum tensile strength, while upright orientation resulted in the lowest ones.



**Figure 8: Stress-Strain curve for 0.1 mm specimens.**

Figure (9) shows stress-strain curve for a 0.2 mm layer thickness has a similar behavior to a 0.1 mm layer thickness where the maximum tensile stress is obtained for 0°. This also occurred for a 0.3 mm layer thickness presented in Figure (10). Consistent results were confirmed for the 45° and 90° where the sudden fracture was maintained compared to more elongation occurred at 0° orientation regardless of layer thickness.

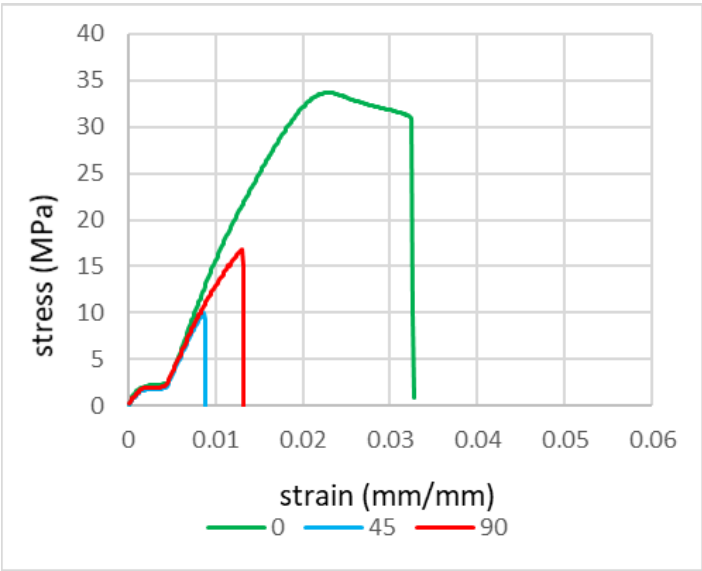


Figure 9: Stress-Strain curve for 0.2 mm specimens.

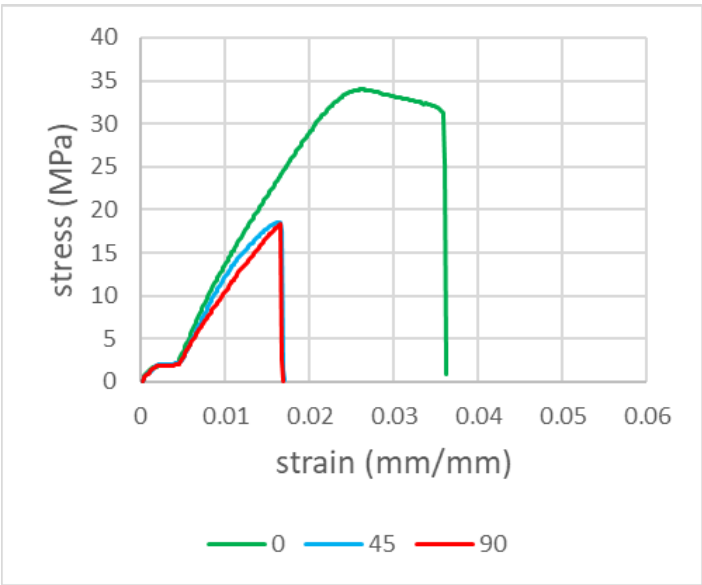
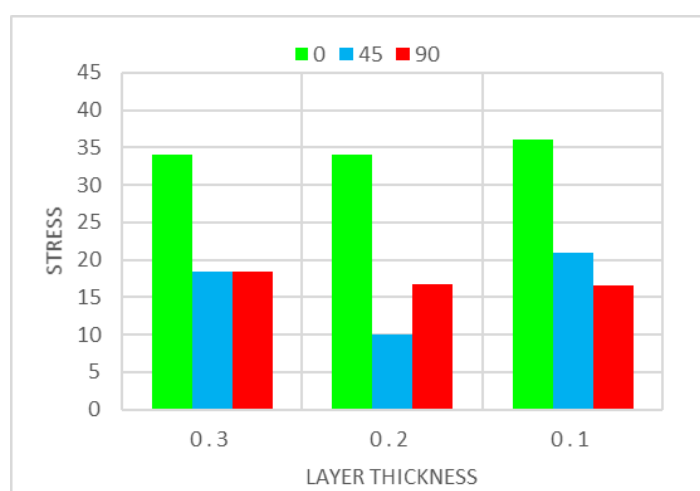


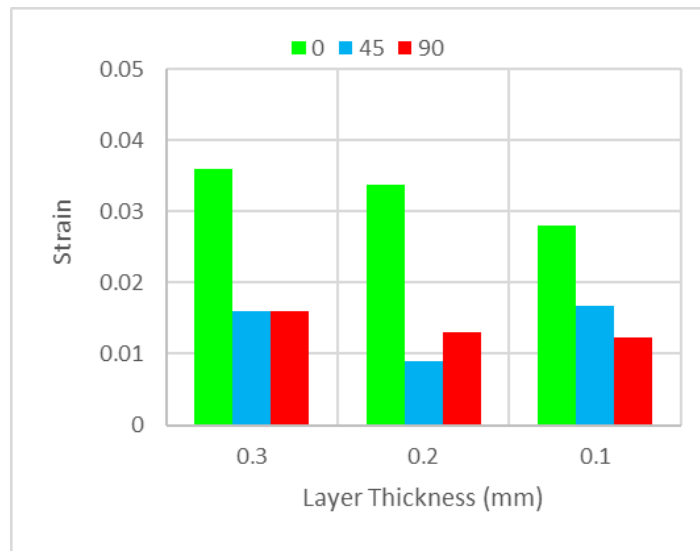
Figure 10: Stress-Strain curve for 0.3 mm specimens.

Figures (11) and (12) summarize stress and strain as a function of layer thickness and orientation. Specimens with  $0^\circ$  orientation exhibit higher stress and strain compared to  $45^\circ$  and  $90^\circ$ . While the layer thickness has a minimal effect on the material strength, it has an important impact on strain, since the strain increases as the layer thickness increases and becomes more pronounced for  $0^\circ$  orientation, and 0.3 mm layer thickness. This is due to the anisotropy arising from the constructing of the 3D printed specimens which depends on the orientation of deposition and way of bonding of layers. Therefore, specimens printed at  $0^\circ$  are aligned along the longitudinal axis of the specimen which maximizes the layer bonding; and the load is parallel and in the direction of long continuous filament strands that carry most of the loads. Consequently, it provides maximum load bearing capacity associated with a large elongation.

In  $45^\circ$  and  $90^\circ$  orientations the tensile loading is perpendicular to the transverse bonded layers results in minimum strength. In addition, printing across the width for  $45^\circ$  and  $90^\circ$  produces an enormous number of layers bonded transversely which may produce micro-voids or weak bonding between layers. This mechanism occurred since the change in specimen orientation will inevitably cause change in building orientation of the layers. For layer thickness, the change in a single layer thickness has insignificant effect on the stress. These results are consistent with the findings in [18] who showed that the tensile strength of PLA printed parts is highly affected by the printing orientation than the layer thickness. They showed the maximum strength was associated with the  $0^\circ$  printing orientation for all layer thicknesses.



**Figure 11: Stress as a function of layer thickness and orientation.**



**Figure 12: Strain as a function of layer thickness and orientation.**

## CONCLUSION

The mechanical behavior of the PLA-3D printed specimens was examined under tensile loading. Two printing parameters were considered, namely, the printing orientation and the printing layer thickness. The results confirm that varying printing parameters significantly influences the mechanical properties. It has been observed that the stress is highly dependent on orientation rather than layer thickness. The maximum stress occurring at  $0^\circ$  orientation was consistent across all thicknesses. On the other hand, strain was more relevant to both orientation and thickness, with a maximum strain associated with a 0.3 mm layer thickness at  $0^\circ$  orientation. It also shows that both printed orientations of  $45^\circ$  and  $90^\circ$  exhibited more brittleness in contrast to  $0^\circ$  printed specimens. These results provide designers with guidelines to control the mechanical properties of PLA parts by choosing the appropriate orientation and layer thickness.

## DECLARATION OF CONFLICTING INTERESTS

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## DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The authors did not use generative AI or AI-assisted technologies in the preparation of this manuscript.

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