Evaluation of Mechanical Properties of FDM-Printed PLA and ABS Polymers

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ABSTRACT: Fused Deposition Modeling (FDM) is a widely adopted technique for polymer fabrication, but the mechanical performance of printed components is dependent on process parameters. While build orientation and layer height have been extensively studied in relation to tensile strength, their influence on hardness remains scarcely explored. This study investigated the influence of layer height (0.12, 0.20, and 0.28 mm) and build orientation (X, Y, and Z) on tensile strength, ductility, and microhardness of PLA and ABS polymers. Tensile testing (ASTM D638) and Vickers microhardness measurements (ASTM E384) were conducted. Statistical analysis was performed using ANOVA with Tukey HSD post hoc testing. Results showed that build orientation was the dominant factor affecting tensile properties, with X- and Y-axis specimens consistently outperforming Z-axis specimens. PLA exhibited a maximum UTS of 45.79 ± 5.15 MPa at 0.28 mm in the X-orientation, while ABS reached 39.19 ± 2.93 MPa at 0.12 mm in the X-orientation. Ductility was higher in X- and Y-orientations (up to 22.33% for ABS) compared to Z (~17%). Microhardness increased with decreasing layer height, with PLA at 0.12 mm in the Y-orientation attaining the highest value of 28.92 ± 1.05 HV. These findings provide practical guidance for optimizing FDM parameters to enhance mechanical performance.

KEYWORDS: 3D printing, Fused Deposition Modeling, layer height, build orientation, hardness, tensile strength.

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I. INTRODUCTION

Fused Deposition Modeling (FDM) is one of the most accessible and widely used Additive manufacturing (AM) techniques for polymer fabrication. Its popularity arises from its operational simplicity, affordability, and ability to produce complex geometries directly from digital designs using a broad range of thermoplastic materials. In FDM, components are built layer by layer by extruding heated thermoplastic through a nozzle according to a digital model. This process enables applications across diverse fields, including prototyping, biomedical devices, consumer products, and functional engineering components (Dey et al. (2021); Cano-Vicent et al. (2021)).

Among the various thermoplastics used in FDM, Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) are the most common. PLA is a plant-based polymer derived from renewable resources such as corn starch and sugarcane. Its biodegradability, low shrinkage, and ease of printing, makes it suitable for packaging and biomedical applications. However, its brittleness and low glass transition temperature (60 °C) limit its structural performance under elevated temperatures. In contrast, ABS, a petroleum derived polymer, offers superior toughness, impact resistance, and thermal stability up to 100 °C, making it ideal for automotive, electronic, and structural applications. Despite these advantages, ABS is prone to thermal warping during printing due to its high volumetric shrinkage upon cooling (Cano-Vicent et al. (2021), Shergill et al. (2023), Sagar et al. (2026)). Moreover, the layer-by-layer deposition inherent to FDM further introduces anisotropy and interlaminar porosity to printed components. These defects often degrade mechanical properties compared to conventionally manufactured parts. Therefore, understanding how printing process parameters influence tensile strength and hardness is essential for improving the structural reliability of FDM printed components.

The mechanical properties of FDM-printed components depend on several processing parameters, including layer height, build orientation, print speed, infill density, and raster angle. These process parameters influence the bonding quality, internal structure, and load-bearing capacity of printed parts, which in turn affect performance in service. Build orientation and layer height have been identified as particularly critical to the tensile strength of printed polymers. The influence of build orientation on tensile strength has been extensively studied. Raut et al. (2014) investigated the influence of nine different build orientations, achieved by changing the rotation angle (0^o, 45^o, 90^o) on the X-, Y-, Z-axis, on tensile strength of ABS printed components. Their study showed that the sample printed in the Y- orientation (printing angle 0^o) exhibited the maximum tensile strength of 35.45 MPa while that printed in the Z - orientation recorded the lowest tensile strength ranging from 17.14 MPa to 22.51 MPa as printing angle changed from 0^o to 90^o. Eryildiz (2021)

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reported that X-axis oriented PLA samples produced at 0º printing angle exhibited the maximum tensile strength of 55.49 MPa while the Z-oriented sample showed about 50% reduction to that of X- oriented samples. Numerous other studies (Hanon et al., 2021, Hiremath et al., 2023; Morettini et al., 2022, Katiyar et al., 2025) have also demonstrated that specimens printed along X- and Y- orientation exhibited higher tensile strength than those printed along Z-axis. This trend is attributed primarily to filament continuity in the loading direction. Z-axis specimens, by contrast, are more susceptible to interlayer delamination because interfacial bonding between layers is weaker than the bulk filament strength. For layer height effects on tensile strength, many authors agree that increasing layer height reduces tensile strength (Zhao et al.,2019, Wang et al., 2020; Sharma et al., 2021; Rankouhi et al., 2016, Altan et al., 2018, Farashi and Vafaee (2021), Shergill et al., (2023)). However, there have been studies that reported inconsistency in this trend. For example, Samykano et al. (2018) investigated the effects of layer height (0.35, 0.40, 0.50 mm), raster angle (45°, 55°, 65°), and infill density (40%, 60%, 80%) on the mechanical properties of FDM-printed ABS, using response surface methodology for optimization. Their results confirmed that 0.4 mm layer height produced the lowest UTS, while 0.35 mm and 0.50 mm layer heigth yielded higher values. Similar results have been reported by Tymrak et al. (2014), Rodríguez-Panes et al., (2018) who demonstrated that UTS at intermediate layer height was the lowest compared to that of the lower and highest layer height. Apart from variability in the trend of lower layer height resulting in higher tensile strength, few authors have reported an opposite trend. Alafaghani et al. (2017) demonstrated that higher layer height resulted in higher UTS in PLA. Similar results were reported by Sood et al. (2010) for ABS. They demonstrated that lower layer height of 0.127 mm resulted in lower UTS compared to 0.254 mm layer height. These discrepancies indicate that the influence of layer height on tensile strength may be dependent on interaction with other process parameters.

While the influence of build orientation and layer height on tensile strength has been extensively studied, the influence of these parameters on hardness has been scarcely explored. Hardness is a key indicator of wear resistance and surface durability, yet few studies have systematically examined its dependence on FDM process parameters. Hanon et al. (2021) investigated the influence of build layer, build orientation and raster angle on hardness of PLA. Their results showed that the effect of build orientation at constant layer height was significant with Y- oriented PLA yielding the highest hardness of 79 shore D hardness, but the effect of layer height exhibited variability with intermediate layer height (0.2 mm) exhibiting 78 shore D hardness while the lowest (0.1 mm) and highest layer height (0.3 mm) exhibited 81 and 80 shore D hardness respectively. Boostan et al. (2025) investigated the effects of build orientation and layer height on PLA, PETG, and PC and reported that specimens oriented along the X-axis consistently exhibited the highest hardness, whereas the influence of layer height varied from one material to another. In contrast, Ramesh and Panneerselvam (2020) and Kumar et al. (2020) observed no significant correlation between layer height and hardness in PLA and carbon fiber–reinforced PETG, respectively. These previous studies indicate that while build orientation shows a consistent and significant effect on hardness across different thermoplastics, the influence of layer height is less predictable and may depend on the type of material. This highlights the need for systematic investigations, particularly on PLA and ABS, the two most widely used FDM materials to determine whether layer height plays a secondary role or interacts with build orientation in influencing hardness. To address this gap, the present study systematically examined the combined effects of build orientation and layer height on the tensile strength and microhardness of FDM-printed PLA and ABS. The novelty of this work lies in its comprehensive evaluation of how these two parameters jointly affect the microhardness behavior of FDM-printed polymers.

II. MATERIALS AND EXPERIMENTAL PROCEDURES

Commercially available Hatchbox™ PLA and ABS filaments were used in this study. Tensile strength specimen was first designed using Autodesk Fusion 360 following ASTM D638 Type IV standard (as shown in Figure 1) for polymer samples with thickness below 4 mm. The CAD models in STL were converted into G-code and the printing parameters were optimised using the Creality Slicer program (Cura-based slicer). Specimens were printed using a Creality Ender 3 printer. 3D Printing was conducted at different build orientation and layer height, while other process parameters as given in Table 1 were held constant. Three samples were printed at different layer heights of 0.12 mm, 0.20 mm, and 0.28 mm and three samples each were printed at X, Y, Z build orientations respectively. Each specimen was inspected against the ASTM D638 Type IV nominal dimensions (given in Figure 1) before testing, and any specimen deviating by more than 0.5 mm was rejected and reprinted. Typical printing issues with FDM (such as ABS warping, nozzle clogging, and bed detachment) were mitigated using a heated bed (100°C for ABS, 60°C for PLA), proper adhesion promoters, nozzle maintenance, and bed re-levelling. All printed specimens were visually inspected to ensure surface integrity before mechanical testing.

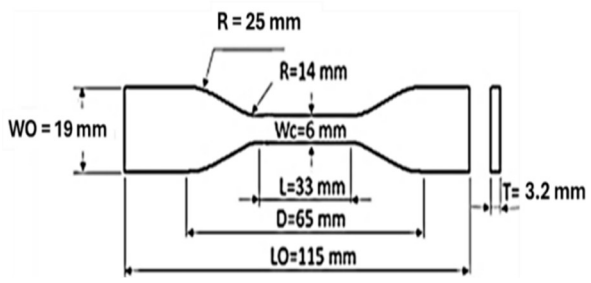


Figure 1 Schematic ASTM D638 Type IV Tensile Test Specimen Dimensions (ASTM, 2012)

Table 1 Printing Parameters used to produce PLA and ABS samples in this study

PROCESS PARAMETER	PLA	ABS
CONTROLLING FACTORS		
Build orientation	X, Y, Z	X, Y, Z
Layer height (mm)	0.12,0.20, 0.28	0.12,0.20, 0.28
FIXED FACTORS		
Infill density (%)	100	100
Infill Pattern	Tri-hexagon	Tri-hexagon
Wall thickness (mm)	1.2	1.2
Print speed (mm/s)	50	50
Filament diameter (mm)	1.75	1.75
Nozzle diameter (mm)	0.4	0.4
Build plate temperature (ºC)	60	100
Print temperature(ºC)	200	240
Build plate adhesion	Raft	Raft
Filament colour	Black	White

Tensile test was performed according to ASTM D638 Type IV standard using a universal tensile machine at a crosshead speed of 5 mm/min. The applied load and extension data were recorded directly from the testing software and used to generate stress–strain curves. From these curves, UTS and percentage elongation at break were determined. Three specimens were tested for each print condition (X, Y and Z), and the average values of UTS and percentage elongation were used to evaluate the effect of layer height, build orientation and hardness on ABS and PLA materials.

Microhardness testing was carried out using a Vickers microhardness tester following ASTM E384 standard. Although Shore D hardness testing (ASTM D2240) is the conventional method recommended for thermoplastics. The Vickers method has been used to measure the hardness of FDM printed polymers by Vorkapić et al (2022), Ramadana et al. (2023) and Rajesh et al. (2023) This method offers the critical advantage of localized measurement on polished cross-sections, which is essential for precisely assessing the anisotropic microstructure and individual printed rasters of FDM-printed PLA and ABS without interference from macro-scale surface roughness. To ensure measurement reproducibility and capture full plastic deformation, indentations were performed using a micro-Vickers diamond pyramid indenter under an applied test load of 100 gf and a dwell time of 10 seconds. Twelve readings were taken per specimen, with the highest and lowest values discarded as outliers and average of the remaining 10 values were used to evaluate hardness. Indentations on PLA and ABS specimens were made in two directions: longitudinal (along the stacking axis) and transverse to the build direction (across the stacking axis) as shown in Figure 2. Measurements were spaced at least three times away from the diagonal indentation to avoid overlapping plastic deformation zones.

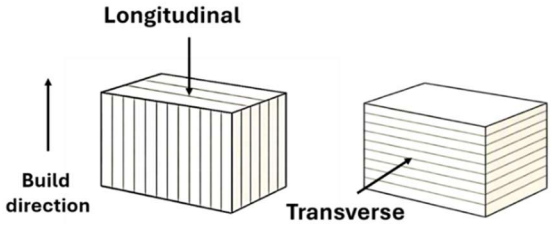


Figure 2 Schematic of microhardness measurement (a) longitudinal direction and (b) transverse direction

Statistical analysis of the results obtained from tensile and microhardness tests were conducted using analysis of variance (ANOVA). The essence of statistical analysis was to establish which of the experimental results were statistically significant with statistical significance defined as $p < 0.05$ for UTS and hardness respectively. All statistical analyses were conducted using Origin Pro. (Origin Lab., USA). Three specimens per condition were tested as earlier stated, while this sample size is sufficient to capture dominant effects, larger sample size would improve statistical confidence for detecting smaller differences.

III. RESULTS AND DISCUSSION

The mechanical performance of FDM-printed components depends on printing process parameters. In this study the combined effect of build orientation and layer heigth, elongation at break and microhardness were systematically analyzed. The results are presented and discussed in the following subsections:

A. Effect of Layer Height on Tensile Strength and Ductility of ABS and PLA Polymers

Figure 3 (a) – (d) presents the UTS and % percentage elongation for ABS and PLA specimens produced at layer heights of 0.12 mm, 0.20 mm, and 0.28 mm. For X-oriented ABS samples, the lowest layer height (0.12 mm) exhibited UTS of 39.19 ± 2.93 MPa, increasing the layer height to 0.20 mm resulted in UTS of 38.11±2.33 MPa, while further increasing layer height to 0.28 mm produced UTS of 34.57 ± 1.88 MPa. In contrast, Y-oriented ABS prints showed improvement, with UTS increasing by approximately 21% at both 0.20 mm and 0.28 mm from the 27.57 ± 2.78 MPa for layer height of 0.12mm. For Z-oriented samples, UTS remained nearly constant across all layer heights. A similar inconsistent trend was observed for % elongation at break (Figure. 3(b)), wherein % elongation of ABS specimens varied with build orientation but was essentially unaffected by layer height, indicating that deformation capacity is largely independent of layer height.

Figure 3 (c) and (d) shows the corresponding results for PLA specimens. The effect of layer height varies with build orientation. In Figure 3 (c), UTS increased as layer height

increased from 0.12 mm to 0.28 mm for X- and Z-oriented samples. Similarly, % elongation increased as layer height increased for these samples as shown in Figure 3(d). Samples built on Y-axis orientation, however, showed a different pattern with UTS almost constant as layer height increased from 0.12 mm to 0.20 mm, while a reduction of about 11% was observed at 0.28 mm. Similar pattern was also observed for % elongation of these samples (Figure 3(d)).

The UTS results for PLA contradicted the well reported trend of the lower the layer height, the higher the UTS but is consistent with that of Alafaghani et al. (2017) who reported that increasing the layer height from 0.1mm to 0.4 mm resulted in about 20% increase in higher UTS. This behavior may be explained by the fact that thicker layers undergo fewer thermal cycles, which reduces residual stress and allows for better molecular diffusion across interfaces. This can enhance inter-layer bonding. Increasing layer height also reduces the number of interlayer boundaries, thereby minimizing discontinuities, voids, and structural defects that often act as stress concentrators leading to improved load bearing and deformation capacity.

Comparing the effect of layer heights on UTS of PLA to ABS, it is apparent that layer height had effect on PLA but not on ABS. This trend agrees with Shergill et al. (2023) and Rodríguez-Panes et al. (2018), who had reported that layer height effect on PLA was more than that of ABS built in the same orientation. Their results, however, showed that as layer height increased UTS decreased.

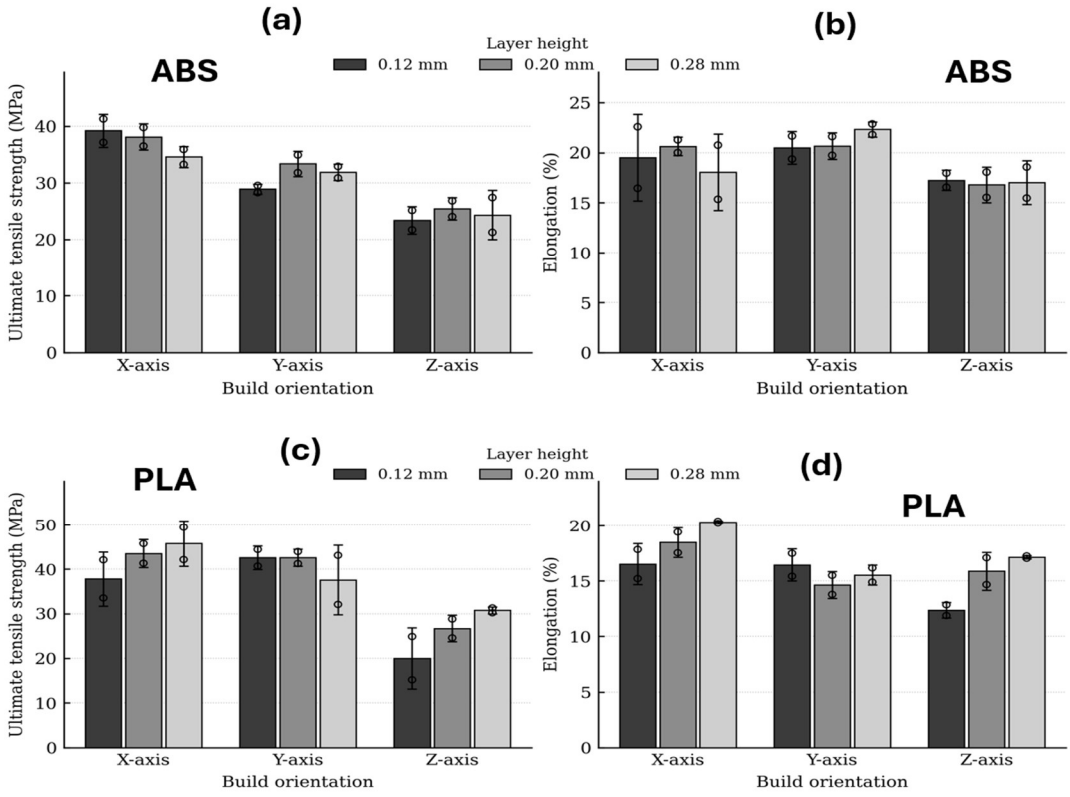


Figure 3 Effects of layer height at constant build orientation on (a) average UTS of ABS (b) average (%) elongation for ABS (c) average UTS for PLA specimens (d) average % elongation for PLA.

B. Effect of Build Orientation on Tensile Strength and Ductility of ABS and PLA Polymers

The relationship between build orientation, tensile strength and ductility for ABS and PLA specimen is presented in Figure 4(a) - (d). For ABS, it is apparent from Figure 4(a) that build orientation is a dominant factor influencing tensile strength. X- and Y-axis oriented specimens consistently exhibited higher tensile strength and ductility compared to Z-axis specimens. At layer height 0.12 mm, X-axis oriented ABS specimens had a UTS of 39.19 ± 2.93 MPa, while about 29.65% and 40% reduction was observed for Y-oriented and Z-oriented samples respectively. This pattern was consistent across all layer heights; for example, at layer height 0.20 mm, X-oriented ABS samples had UTS of 38.12 ± 2.33 MPa while those produced along Z-axis specimens had UTS of 25.44 ± 1.97MPa. The lower UTS of Z-oriented samples is attributed to weak interlayer adhesion and the ease of crack propagation along layer boundaries, whereas samples produced along X and Y orientations benefited from continuous filament alignment along the load path, enabling improved stress

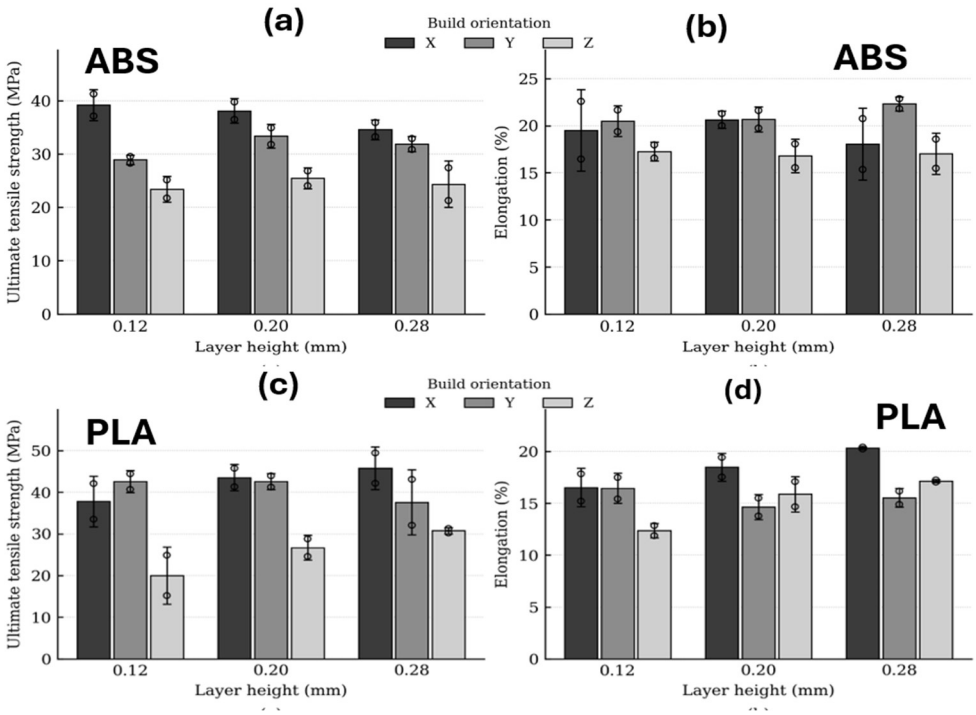


Figure 4 Effect of build orientation on FDM printed polymers at constant layer height (a) average UTS and (b) average % elongation for FDM printed ABS (c) average UTS for PLA (d) average % elongation of for FDM printed PLA.

transfer and plastic deformation before failure. Figure 4 (b) showed that ductility was higher for X- and Y- oriented samples (19.51% and 21.60%) than for Z-oriented samples (17.25%). However, no consistent trend was observed as build orientation varied at any given layer height. For instance, at layer height 0.12 mm, % elongation increased from 19.52±4.33% for X-oriented samples to 21.59 ± 0.09% for Y-oriented samples and then decreased to 17.26 ±1.00 % for Z-oriented samples respectively. Similarly at a higher layer height of 0.28mm, % elongation ranged from 18.05 ± 3.82 % for X-oriented samples, 22.33 ± 0.75 % for Y-oriented and 17.02 ± 2.19 % for Z-oriented samples, thus showing no consistent trend as orientation changed.

For PLA samples as presented in Figure 4 (c), X- and Y-oriented samples exhibited UTS of 37.81 ± 6.06 MPa and 42.55 ± 2.65 MPa respectively while Z-oriented samples exhibited 20.04 ± 6.85 MPa. In contrast to the trend observed with ABS samples, the performance of X- and Y-oriented PLA specimens was not uniform: at layer height 0.12mm, X samples demonstrated lower UTS than Y-oriented samples. At layer height 0.28 mm, an opposite trend was observed while at 0.20 mm, similar values were recorded. Identical pattern of incontinency was observed with ductility of Y- and Z-axis samples as shown in Figure 4 (d). At all layer heigth, X oriented sample exhibited the highest ductility with ductility increasing as layer height increased.

Comparing the mechanical properties of ABS and PLA as presented in Figure 4, It is apparent that build orientation influenced the UTS of ABS and PLA samples. PLA, however, attained higher UTS values than ABS at layer height 0.20 mm and 0.28 mm except at 0.12 mm layer heigth. This observation agrees with Syaefudin et al. (2023), Vikneswaran et al. (2022) and Özsoy et al. (2021) who all reported a higher UTS for PLA than ABS at constant layer height. Furthermore, it can be inferred from Figure 4 (a) & (c) that Z-oriented samples produced the lowest UTS compared to that of X- and Y-oriented samples at the same layer height. This trend is consistent with studies by Hanon et al. (2021), Eryildiz (2021), Katiyar et al. (2025). They evaluated UTS of ABS and PLA under different printing parameters and reported that Z-oriented samples produced the lowest UTS. This behavior is attributed to how tensile load interacts with the layered structure. In the X and Y orientations, loads act parallel to the layers (as schematically shown in Figure 5) and failure occurs primarily through bulk material fracture involving polymer chain breakage, a mechanism that allows both ABS and PLA components to achieve strengths approaching their intrinsic material properties (Tymrak et al., 2014, Wang et al. 2020) hence they can sustain greater loads and undergo yielding before failing by intralayer fracture. On the other hand, Z-axis behavior is governed almost entirely by interlayer adhesion because tensile loads act perpendicular to the layer interfaces, each boundary becomes a potential plane for interlayer fracture as shown in Figure 5. Optical microstructural evaluation of the fractured ABS and PLA samples shown in Figure 6 support this fracture mode.

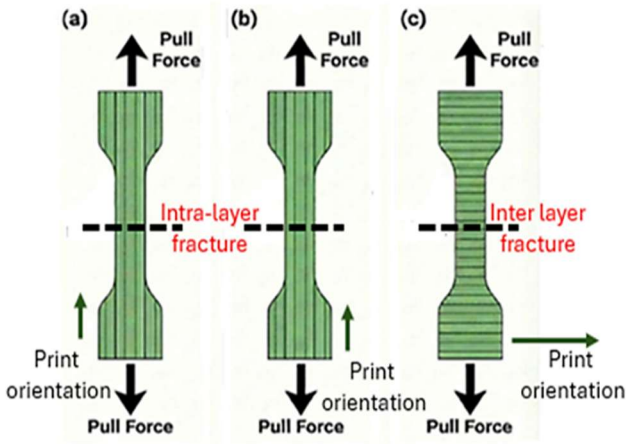


Figure 5 Schematic Tensile failure mechanism at (a) X-axis (b) Y-axis and (c) Z-axis oriented FDM specimen (Adapted from Eryildiz (2021)

. Optical micrographs of X- and Y- oriented specimens for both ABS and PLA (Figure 6) exhibited rough, fibrous fractured surfaces typical of mixed mode ductile failure. In contrast, the Z-axis specimens exhibited a smooth, planar fractured path aligned with layer boundaries, typical of brittle interlayer delamination separation.

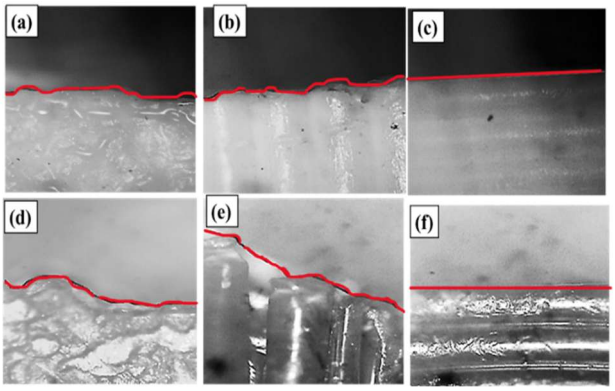


Figure 6 Optical micrography of fractured surfaces of (a) ABS X-axis (b) ABS Y-axis (c) ABS Z-axis. (d) PLA X-axis (e) PLA Y-axis (f) Z-axis (Magnification 100X)

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Table 2 Microhardness Measured Parallel and Traverse to the Build Axis

Layer Height (mm)	Build Orientation	Hardness longitudinal to the Build Axis (HV)		Hardness transverse to the Build Axis (HV)	
		ABS	PLA	ABS	PLA
0.12	X-axis	22.89 ± 0.44	25.66 ± 0.56	22.64 ± 0.58	24.73 ± 0.29
0.20	X-axis	22.21 ± 0.49	25.46 ± 0.41	21.07 ± 0.51	24.03 ± 0.38
0.28	X-axis	18.33 ± 0.57	25.10 ± 0.54	18.36 ± 0.81	23.92 ± 0.64
0.12	Y-axis	24.96 ± 0.66	28.22 ± 0.65	25.91 ± 0.56	28.92 ± 1.05
0.20	Y-axis	23.44 ± 0.76	27.86 ± 0.69	24.84 ± 0.85	27.80± 0.32
0.28	Y-axis	21.37 ± 0.57	27.27 ± 0.79	20.31 ± 0.95	27.48 ± 0.40
0.12	Z-axis	23.14 ± 0.56	27.48 ± 0.83	24.86 ± 0.51	28.26 ± 1.04
0.20	Z-axis	21.89 ± 0.49	26.15 ± 0.35	22.09 ± 0.67	27.38 ± 0.28
0.28	Z-axis	21.33 ± 0.53	25.85 ± 0.59	21.16 ± 0.46	27.05 ± 0.77

Table 3 Analysis of variance for UTS of ABS and PLA samples

Material	Source of variation	df	F	p	Partial η^2
ABS	Build orientation	2	36.80	< 0.001	0.800
ABS	Layer height	2	1.36	0.305	0.030
ABS	Orientation × layer height	4	1.67	0.241	0.073
ABS	Residual	9			
PLA	Build orientation	2	22.54	< 0.001	0.706
PLA	Layer height	2	1.71	0.234	0.054
PLA	Orientation × layer height	4	1.58	0.260	0.099
PLA	Residual	9			

C. Effect of build orientation and layer height on microhardness of ABS and PLA

The microhardness of ABS and PLA specimens produced at different layer heights and build orientations is presented in Table 2. Microhardness of both PLA and ABS showed dependence on both layer height and build orientation. Across X-,Y-,Z- orientations, increasing layer height resulted in reduction of hardness values indicating that lower layer height (0.12 mm) enhanced surface densification and resistance to indentation. For example, Y-oriented ABS samples printed at layer height of 0.12 mm exhibited the highest hardness (25.91 ± 0.56 HV transverse), while it decreased to 20.31 ± 0.95 HV at 0.28 mm layer height Similarly, PLA exhibited maximum hardness of 28.92 ± 1.05 HV (Y-axis, transverse, 0.12 mm), with reductions at higher layer heights. This observation may be attributed to thinner layers producing smoother surfaces with less pronounced layer boundaries and reduced surface roughness (Bintara et al. (2021). Smoother surfaces with fewer irregularities may exact higher hardness values than rougher surfaces yielding lower hardness values. Also, the cooling rate differences between layer heights could also influence surface hardness. Thinner layers cool more rapidly due to their smaller thermal mass, potentially increasing the crystalline fraction in semi-crystalline PLA or creating denser amorphous regions in ABS. This microstructural densification near the surface could enhance hardness in specimens with lower layer height.

It can also be observed from Table 2 that Y-oriented specimens consistently had higher microhardness values than X- and Z-axis builds. This trend was observed in both longitudinal and transverse directions, highlighting the influence of interlayer bonding and load distribution relative to the print axis. Z-axis specimens generally showed lower hardness, reflecting weaker interlayer cohesion when indentation was applied perpendicular to the deposited layers. Comparing these results to previous works showed that our results do not agree with the findings of Hanon et al. (2021) and Ramesh and Panneerselvam (2020) who reported that only build orientation had effect on hardness of PLA with layer height showing no consistent trend. The discrepancy may be attributed to differences in material systems, printing parameters, or measurement protocols, thus highlighting the complexity of layer height effects hardness in FDM printing.

Table 2 further showed that PLA consistently exhibited higher hardness values than ABS across all conditions, underscoring its superior resistance to localized deformation. This result agrees with that of Sagar et al. (2026), wherein hardness of PLA was consistently higher than ABS even when infill density varied from 0% to100%. The higher hardness of PLA is expected and can be attributed to the semi-crystalline nature of PLA compared to the amorphous nature of ABS. Its crystalline regions contribute to greater rigidity and resistance to localized deformation under indentation. In contrast, ABS is an amorphous polymer with enhanced toughness and impact resistance rather and lower resistance to localized indentation. longitudinal ones, particularly in Y-oriented samples (e.g., PLA: 28.92 ± 1.05 HV (transverse), 28.22 ± 0.65 HV (longitudinal) at 0.12 mm layer height). This suggests that the indenter, when applied transversely, engages multiple interlayer interfaces and distributes stress across stacked filaments, thereby enhancing localized resistance to deformation. In contrast, longitudinal measurements align more closely with filament direction, making them more sensitive to interlayer weaknesses and micro-voids.

D. Statistical analysis of the influence of build orientation and layer height on tensile strength and microhardness of PLA and ABS

UTS data presented in Figures 2 and 3 for ABS and PLA specimens were tested with analysis of variance (ANOVA) to determine which of the relationship between build orientation and layer height from the experimental data were statistically significant.

The ANOVA test result shown in Table 3 confirmed that build orientation had dominant influence on UTS for both ABS and PLA specimens ($p < 0.001$), with large effect sizes ($\eta^2 = 0.800$ and 0.706 respectively). In contrast, layer height did not significantly affect UTS (ABS: $p = 0.305$; PLA: $p = 0.234$), nor was the interaction between orientation and layer height (ABS: $p = 0.241$; PLA: $p = 0.26$). While this aligns with the descriptive data for ABS, it does not agree with the descriptive data presented in Figure 3 for PLA, indicating variability across replicates was too high for these differences to be considered. statistically reliable. In other words, the apparent increase in UTS for X and Z build orientations and decrease for Y orientation may reflect random variation rather than a consistent interaction effect. Tukey HSD comparisons (presented in Table 4) indicated that UTS varied significantly across build orientations, with X-oriented specimens consistently outperforming Y- and Z-axis builds. In general, PLA achieved higher UTS than ABS, with maximum values of 45.79 ± 5.15 MPa at 0.28 mm layer height, compared to 39.19 ± 2.93 MPa for ABS at 0.12 mm.

Table 5 shows the ANOVA result for microhardness. Both build orientation and layer height were statistically significant for ABS and PLA ($p < 0.001$). Hardness decreased as layer height increased, with Y-orientation yielding the highest values (PLA: 28.92 ± 1.05 HV; ABS: 25.91 ± 0.56 HV at 0.12 mm). Statistical analysis further indicated that indentation direction was significant for ABS ($p = 0.047$) but not for PLA ($p = 0.541$), highlighting that the effect of indentation is material-dependent and secondary in magnitude. In summary, whilst indentation direction can influence measured hardness values, particularly in ABS, its effect is small compared to the pronounced effects of build orientation and layer height. Thus, hardness measurements in either direction provide consistent trends, with transverse values offering a slightly more conservative estimate of surface resistance. Tukey HSD post-hoc comparisons presented in Table 6 corroborates these findings. For ABS, all group comparisons (X vs Y, X vs Z, Y vs Z) were statistically significant ($p < 0.01$). Layer height comparisons revealed consistent reductions in hardness with increasing

layer height: 1.48 HV between 0.12 mm and 0.20 mm ($p < 0.001$), −3.92 HV between 0.12 mm and 0.28 mm ($p < 0.001$), and −2.45 HV between 0.20 mm and 0.28 mm ($p < 0.001$). For PLA, group comparisons were also significant ($p < 0.001$). Layer height effects were weaker, with significant differences between 0.12 mm and 0.20 mm (−0.77 HV, $p = 0.019$) and 0.12 mm and 0.28 mm (−1.10 HV, $p < 0.001$), but no significant difference between 0.20 mm and 0.28 mm (−0.34 HV, $p = 0.458$). In summary, these findings underscore that build orientation is the primary factor governing both UTS and hardness in FDM printed polymers, while layer height plays a secondary but important role in hardness optimization. The results highlight the need to prioritize build orientation control in design and fabrication, with layer height adjustments serving as a complementary strategy for enhancing surface durability

Table 4 Tukey HSD comparisons for UTS of ABS and PLA samples

Material	Comparison	Mean difference (MPa)	p adjusted	Significant
ABS	X vs Y	−6.36	0.005	Yes
ABS	X vs Z	−12.88	< 0.001	Yes
ABS	Y vs Z	−6.52	0.004	Yes
ABS	0.12 vs 0.20 mm	2.24	0.817	No
ABS	0.12 vs 0.28 mm	0.20	0.998	No
ABS	0.20 vs 0.28 mm	−2.04	0.845	No
PLA	X vs Y	−1.47	0.881	No
PLA	X vs Z	−16.55	< 0.001	Yes
PLA	Y vs Z	−15.08	0.001	Yes
PLA	0.12 vs 0.20 mm	4.14	0.735	No
PLA	0.12 vs 0.28 mm	4.58	0.687	No
PLA	0.20 vs 0.28 mm	0.44	0.997	No

Table 5: ANOVA test result for microhardness of PLA and ABS

Material	Source of variation	df	F	p	Partial η^2
ABS	Build orientation	2	252.67	< 0.001	0.241
ABS	Layer height	2	602.10	< 0.001	0.575
ABS	Indentation direction	1	4.01	0.047	0.002
ABS	Orientation × layer height	4	29.17	< 0.001	0.056
ABS	Orientation × direction	2	12.00	< 0.001	0.012
ABS	Layer height × direction	2	13.99	< 0.001	0.013
ABS	Orientation × layer height × direction	4	12.76	< 0.001	0.024
	Residual	162			
PLA	Build orientation	2	383.32	< 0.001	0.674
PLA	Layer height	2	47.61	< 0.001	0.084
PLA	Indentation direction	1	0.38	0.541	< 0.001
PLA	Orientation × layer height	4	2.18	0.074	0.008
PLA	Orientation × direction	2	48.81	< 0.001	0.086
PLA	Layer height × direction	2	0.69	0.502	0.001
PLA	Orientation × layer height × direction	4	1.37	0.248	0.005
	Residual	162			

Table 6 Tukey HSD post-hoc comparisons for ABS and PLA

Material	Comparison	Mean difference (HV)	p adjusted	Significant
ABS	X vs Y	2.56	< 0.001	Yes
ABS	X vs Z	1.50	< 0.001	Yes
ABS	Y vs Z	−1.06	0.006	Yes
ABS	0.12 vs 0.20 mm	−1.48	< 0.001	Yes
ABS	0.12 vs 0.28 mm	−3.92	< 0.001	Yes
ABS	0.20 vs 0.28 mm	−2.45	< 0.001	Yes
PLA	X vs Y	3.11	< 0.001	Yes
PLA	X vs Z	2.21	< 0.001	Yes
PLA	Y vs Z	−0.90	< 0.001	Yes
PLA	0.12 vs 0.20 mm	−0.77	0.019	Yes
PLA	0.12 vs 0.28 mm	−1.10	< 0.001	Yes
PLA	0.20 vs 0.28 mm	−0.34	0.458	No

IV. CONCLUSION

This study examined the effects of build orientation and layer height on the tensile strength and microhardness of FDM-printed PLA and ABS polymers. The results showed that build orientation is the dominant factor influencing mechanical performance, with X- and Y- oriented specimens consistently showing higher tensile strength and ductility compared to Z- oriented samples for both PLA and ABS polymers. In contrast, layer height did not significantly affect tensile strength but had a measurable influence on hardness, with lower layer heights producing higher microhardness values. These findings demonstrate that optimizing build orientation is critical for improving structural reliability, while layer height adjustments can be used to tailor surface hardness. The study provides practical guidance for selecting FDM process parameters to enhance the mechanical performance of PLA and ABS components.

AUTHOR CONTRIBUTIONS

A. M. Oladoye: Writing – revised and final draft, project co-supervision. **C. Mekwunye:** Experimentation, writing: original draft. **O. V. Ibrahim** – Experimentation, writing: revised and original draft, ANOVA analysis, A**. Fadipe**: Experimentation, **P. Utti**: Experimentation **L. O. Osoba:** Conceptualization, writing: review, project supervision.

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