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The influence of the raster angle on the dimensional accuracy of FDM-printed PLA, PETG, and ABS tensile specimens

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Abstract: 3D printing is a rapidly developing manufacturing method that produces objects in layers. Fused Deposition Modelling (FDM) is a 3D printing technology where the material is melted in a hot nozzle and placed on a build platform to create a prototype layer by layer. In this study, the effects of different raster angles (0°, 45°, 90°, 45°/-45°, 0°/90°) on dimensional accuracy for PLA, PETG, and ABS materials produced using FDM were investigated. The results revealed that PETG generally shows higher dimensional deviations than PLA and ABS. Samples with a raster angle of 90° typically have lower deviation percentages than other angles. Width deviations (approximately 1.5% on average) were lower than thickness deviations (about 9.5% on average). Analysis of the cross-sectional areas shows that all samples are above the theoretical area (41.6 mm^2). PETG samples with a raster angle of 45°/-45° exhibit the largest cross-sectional area (46.78 mm^2), while ABS samples with a raster angle of 90° exhibit the smallest (45.46 mm^2). This study is essential to understand the impact of material selection and raster angle on dimensional accuracy, and it is recommended to account for cross-sectional deviations and calculate the stress based on the actual cross-sectional area to achieve more accurate results in applications requiring precise measurements. These data offer valuable information for those interested in 3D printing and its professionals and can lead to further research in this field so that printing techniques can be further developed and product quality can be improved.

Keywords: Dimensional accuracy, raster angle, FDM, PLA, PETG, ABS

1. Introduction

3D printing is a rapidly advancing manufacturing technique that produces parts in layers. 3D printing uses 3D computer-aided design (CAD) data to convert it directly into a physical prototype. Most 3D printing methods involve dividing a computer-aided design (CAD) model into successive 2D layers and constructing the prototype by layering them one upon another. This technology has distinct advantages over traditional manufacturing techniques, such as producing very complex geometries, assembled functional parts, lattice structures, and multi-material components without tooling [1–5].

Fused deposition modeling (FDM) is a widely embraced additive manufacturing (AM) technique for producing three-dimensional components. It involves depositing material layer by layer using a plasticizing nozzle that moves in the X-Y plane. In this process, a material filament is melted in a heated nozzle and deposited on a building platform. This nozzle is moved in the XY plane using a 3-axis motion system and prints a prototype layer. Once a layer is finished, the build platform descends by one increment, referred to as the slice thickness, in the Z direction, and the sequence is reiterated for the subsequent layer until the entire model is constructed [6–9].

Previous studies examining the dimensional accuracy of parts produced by FDM are included in this paragraph. Frunzaverde et al. [10] examined FDM-printed PLA tensile specimens, exploring the impact of filament color. They varied layer heights (0.05 mm, 0.10 mm, 0.15 mm, 0.20 mm) and filament colors (natural, black, red, grey). Results showed color significantly affected both dimensions and tensile strength. The two-way ANOVA revealed PLA color (η^2 = 97.3%) as the dominant factor for strength, followed by layer height (η^2 = 85.5%) and their interaction (η^2 = 80.0%). Black PLA excelled in dimensional accuracy (0.17% width, 5.48% height), while grey PLA exhibited high tensile strength (57.10 MPa to 59.82 MPa) under identical conditions. Bolat and Ergene [11] studied how filament type and layer height affect dimensional accuracy in 3D printed tensile test samples (PLA, PET-G, ABS) using Fused Filament Fabrication (FFF). Varying layer heights (0.2 mm, 0.3 mm, 0.4 mm) maintained consistent parameters, except for nozzle and platform temperature. They measured length, width,

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and height, comparing results with design dimensions. PLA had the best surface quality, while PET-G excelled in length and height accuracy. Tezel's study [12] explores additive manufacturing, which is vital in machine design and part production. A popular method, FDM uses polymers like ABS, PLA, and PET-G, impacting part strength and surfaces. Precise 3D printing relies on parameters like speed and temperature. PET-G samples (hollow and solid), 5-15 mm diameter, were made with FDM, varying temp (220°C, 240°C) and speed (30 mm/s, 40 mm/s) to assess dimensional accuracy, highlighting temperature's impact. Stojković et al. [13] focused on PLA, PETG, and carbon fiber-reinforced PETG in 3D printing. They investigated annealing's impact on tensile strength and dimensions, varying layer heights (0.1 mm, 0.2 mm, 0.3 mm), and annealing conditions (60–100°C, 30–90 min). Regression models highlighted layer height's dominant effect on strength. Optimal settings were determined for each material. PETGCF showed minimal dimensional changes and the best elasticity. This study adds crucial insights to the annealing discussion in 3D printing. Akbaş et al. [14] studied nozzle temperature and feed rate effects on FDM part dimensional accuracy with ABS and PLA. They used both simulations and experiments with varying parameters. PLA outperformed ABS in accuracy. Higher nozzle temps increased PLA strip width, but effects were mixed for ABS. Increased feed rates reduced strip width. A regression model ranked the importance of measurement position, feed rate, and nozzle temp. Finite element modeling accurately predicted polymer swell. Future work includes refining three-dimensional modeling with non-symmetric conditions. Mohanty et al. [15] optimized ABS M30 parts using FDM and the MARCOS Method, establishing purposeful dimension relationships. Findings favored a part orientation of a 30°, a layer thickness of 0.127 mm, 30° raster angle, 0.004 mm air gap, and 0.5064 mm raster width via ten nature-inspired meta-heuristic methods. Component orientation played a pivotal role in ensuring FDM-built item dimensional accuracy. This study enhances FDM optimization, elevating component construction quality by considering diverse process constraints and complex geometric factors. Çakan's study [16] on FDM revealed that varying raster angles significantly impact polymer filament parts. The ultimate tensile strength decreased with increasing raster angle, peaking at 0° for maximum strength. Additionally, ±45° angles exhibited the highest ductility, with fracture mechanisms dependent on raster orientation. Tanoto et al. [17] investigated FDM 3D printing using ABS plastic, assessing machine parameters' impact on outcomes. They explored three deposit orientations (XY, YX, ZX), measuring processing time, dimensional accuracy, and strength. The third orientation was the fastest (2432 seconds), followed by the first and second. Dimensional accuracy varied compared to ASTM 638-02 standards. Tensile tests revealed the second orientation with the highest strength (7.66 MPa), followed by the first and third (6.8 MPa and 3.31 MPa, respectively). This research highlights the influence of process parameters on 3D printing.

In the present study, tensile specimens with different raster angles (0°, 45°, 90°, 45°/-45°, 0°/90°) were produced according to ASTM D638-I standard using FDM technology. Five different raster angles were applied for PLA, PETG, and ABS materials. This study mainly investigates the effects of raster angle on the dimensional accuracy of tensile specimens for three different materials.

2. Material and Method

In this study, Creality brand CR-PLA, CR-PETG, and CR-ABS filaments are the materials used in sample production. All filaments are 1.75 mm in diameter. PLA, PETG, and ABS filaments are white, yellow, and grey, respectively. Due to their widespread use, these filaments were preferred as test materials [18].

The printing processes of the samples were carried out using a Creality Ender3 S1 Pro 3D printer. This printer allows a print size of 220x220x270mm. The maximum nozzle temperature of the 3D printer is 300 °C, the maximum table temperature is 110 °C, and the maximum printing speed is 150 mm/s. The test specimens used in the study were first designed in the Solidworks 2020 CAD program in accordance with the dimensions specified in ASTM D638–I [19]. Figure 1 shows the dimensions of the ASTM D638 standard type I test specimen on the technical drawing. The designed specimen geometry was converted to ".stl" file format and transferred to the CURA 5.4.0 program. CURA 5.4.0 program is used to create the G codes required for the 3D printer. In addition, thanks to this program, different manufacturing parameters can be determined with the 3D printer [20]. The fixed parameters used in the study are shown in Table 1. As the printing temperature, the middle value of the temperature range specified by the manufacturer was selected for all three filaments. The 3D printer and the image of the samples produced according to ASTM D638-I are given in Figure 2.

Sample width and thickness measurements were taken from the marked points shown in Figure 1 to evaluate the

Table 1. Printer, slicing program, and fixed parameters used in the experiments.

3D Printer	Creality Ender3 S1 Pro
Slicing Program	Ultimaker Cura
Printing Temperature (°C)	PLA:210, PETG:240 ABS:260
Built Plate Temperature (°C)	PLA:60, PETG:70, ABS:110
Infill Density (%)	100
Infill Pattern	Lines
Layer Height (mm)	0.2
Print Speed (mm/s)	60
Nozzle Diameter (mm)	0.4
Wall Line Count	1
Top/Bottom Thickness (mm)	0.1
Fan Speed (%)	100

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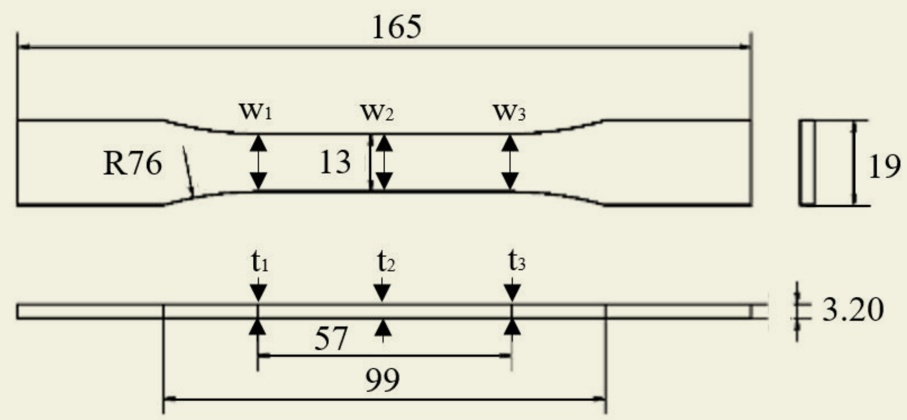

Figure 1. The CAD geometry of the printed samples with the positions of the dimensional accuracy measurements (w_1, w_2, w_3-width measurements; t_1, t_2, t_3- thickness measurements)

dimensional accuracy. The measurements were carried out with a KMP brand digital micrometer with a measuring width of 150 mm and an accuracy of ±0.01 mm. For each specimen, measures were taken for widths w_1, w_2 and w_3 and thicknesses t_1, t_2 and t_3. Three specimens were produced for each raster angle parameter, and w and t measurements were made for all three specimens (Figure 3). The mean and standard deviation values of the width and thickness measurements were calculated for each sample. Dimensional accuracy percentages and standard deviation values of these percentages were also calculated by considering the average results of three samples produced for each parameter result. Since the cross-sectional area in the tensile test is used as the basis for stress calculation, the w (mm) x t (mm) values (mm^2) were also calculated, and the deviation of the area from the theoretical area was revealed.

3. Results and Discussion

This section gives width and thickness measurements varying with raster angle, and various dimensional accuracy calculations are made based on these measurements. The dimensional deviation percentages obtained as a result of the calculations are graphed. The graphical data allows us to compare the dimensional accuracy output varying with different material groups and raster angles. Sample width (w_1, w_2 and w_3) and thickness (t_1, t_2 and t_3) measurements were obtained from the measurement points shown in Figure 1. The raw results obtained from the measurements are given in Table 2.

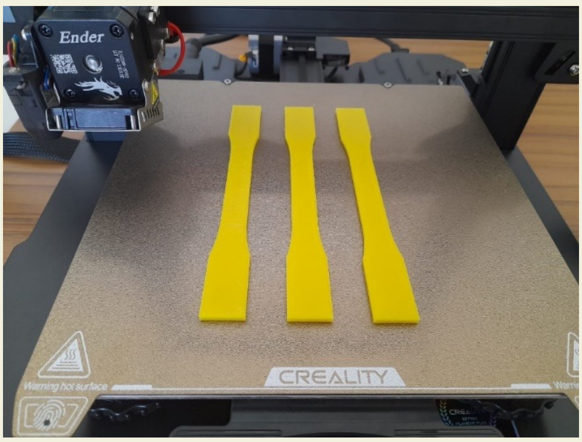

Figure 2. Image of some sample tensile specimens produced by 3D printer.

Table 2 was used to calculate the width deviation varying with raster angle. Firstly, average widths were determined. The percentage deviation of these average widths from the theoretical width of 13 mm was calculated. The changing percentage deviations and the standard deviation values of these deviations are illustrated in Figure 4. In Figure 4, the y-axis scale was changed between 0-14% to be compatible with the thickness scale. The lowest average width value was 13.10 mm for the sample with PLA 45° raster angle, and the highest average width value was 13.27 mm for the sample with PETG 45°/-45° raster angle (Table 2). The width deviation ratio between the samples with the lowest and highest average widths varied between 0.79-2.08% (Figure 4). When Figure 4 is analyzed, it is seen that the width deviation in PETG measurements is higher than PLA and ABS. The average width measurement (mm) of the PETG sample is approximately 0.7% and 0.09 mm higher than the PLA and ABS samples. The percentage of width deviation (%) for PLA, PETG, and ABS specimens is in the order of PETG, ABS, and PLA, starting from the highest. The percentage of width deviation (%) for raster angles are in the following order, starting from the largest: 0°, 45°/-45°, 0°/90°, 90° and 45°. There is a difference of approximately 32% between the deviation rates (%) of the samples with 0° raster angle, which shows the highest percentage deviation, and the samples with 45° raster angle, which shows the lowest percentage deviation. If we look at the effect of the raster angle on the width deviation for each material individually, the highest deviation for PLA is 0°, the lowest deviation is 45°, the highest deviation for PETG is 45°/-45° and the lowest deviation is 45°, the highest deviation for ABS is 0° and the lowest deviation is 90°. This shows that the effects of raster angle on the width deviation are dissimilar in different materials.

The percentage deviations of the measured sample thicknesses with respect to the theoretical thickness of 3.2 mm are given in Figure 5. In the average thicknesses calculated based on Table 2, the highest thickness value is 3.55 mm for the PLA sample with a 45° raster angle, and the lowest is 3.47 mm for the PLA sample with a 0° raster angle. When Figure 5 is analyzed, it is seen that there are very small differences between the material and the varying thickness averages. The average thickness values in mm are PLA, PETG, and ABS, ranging from large to small. Percentage thickness deviations generally varied around 9.5%. In terms of raster angle, the percentage deviations are ranked as 45°, 0°/90°, 45°/-45°, 90°, and 0° starting from the largest. While the average percentage deviation of three different materials for 45° is 10.32%, this rate is 9.06% for 0°. While the length deviation rate was around 2% in width measurements, it was observed that it increased considerably in thickness measurements, rising to around 10%. If we look at the effect of raster angle on thickness deviation for each material individually, the highest deviation for PLA is 45°, the lowest deviation is 0°, the highest deviation for PETG is 0°/90°, and the lowest deviation is 0°, the highest deviation for ABS is 0° and the lowest deviation is 90°. For ABS, the highest deviation is 0°, and the lowest deviation is 90° in both width and thickness measurements. For PLA, the highest deviation angle of 0° in width measurements showed the lowest deviation angle in thickness measurements, and the lowest deviation angle of 45° in width measurements showed the highest deviation angle in thickness measurements.

In order to evaluate and visualize the overall effect of sample thickness and width on dimensional accuracy, average cross-sectional areas varying with raster angle are shown in Figure 6. The average cross-sectional area in all samples is greater than the theoretical cross-sectional area of 41.6 mm^2. While the largest cross-sectional area is 46.78 mm^2 in the PETG sample with a raster angle of 45°/-45°, the lowest cross-sectional area is 45.46 mm^2 in the ABS sample with a raster angle of 90°. When the average cross-sectional areas for all specimens are ranked according to the raster angle, the order from largest to smallest is 45°, 0°-90°, 45°-45°, 0° and 90°. When the area deviation is considered as the average of the three samples in general, the lowest deviation was at 90 degrees. PLA, PETG, and ABS were at 0°, 0°, and 90°, respectively. When the averages of the cross-sectional areas varying with the raster angle are considered material differences, the order of the area is PETG, PLA, and ABS from large to small.

Cross-section deviations in percentage terms are shown in Figure 7. In percentage terms, the deviation rate generally varied around 11.5%. The highest percentage deviation is 12.45% for the sample with PETG 45°/-45° raster angle, and the lowest percentage deviation is 9.28% for the sample with ABS 90° raster angle. The lowest percentage deviations of the cross-sectional area for PLA, PETG, and ABS materials are 9.71%, 10.72%, and 9.28% for 0°, 0°, and 90° raster angles, respectively. When the cross-sectional area is taken as the theoretical value in the tensile test, the stress value will be approximately 10% higher than in reality. For this reason, taking into account the cross-sectional deviations in the production of the materials used in the study with a 3D printer and calculating the stress according to the actual cross-sectional area will enable us to obtain more accurate results.

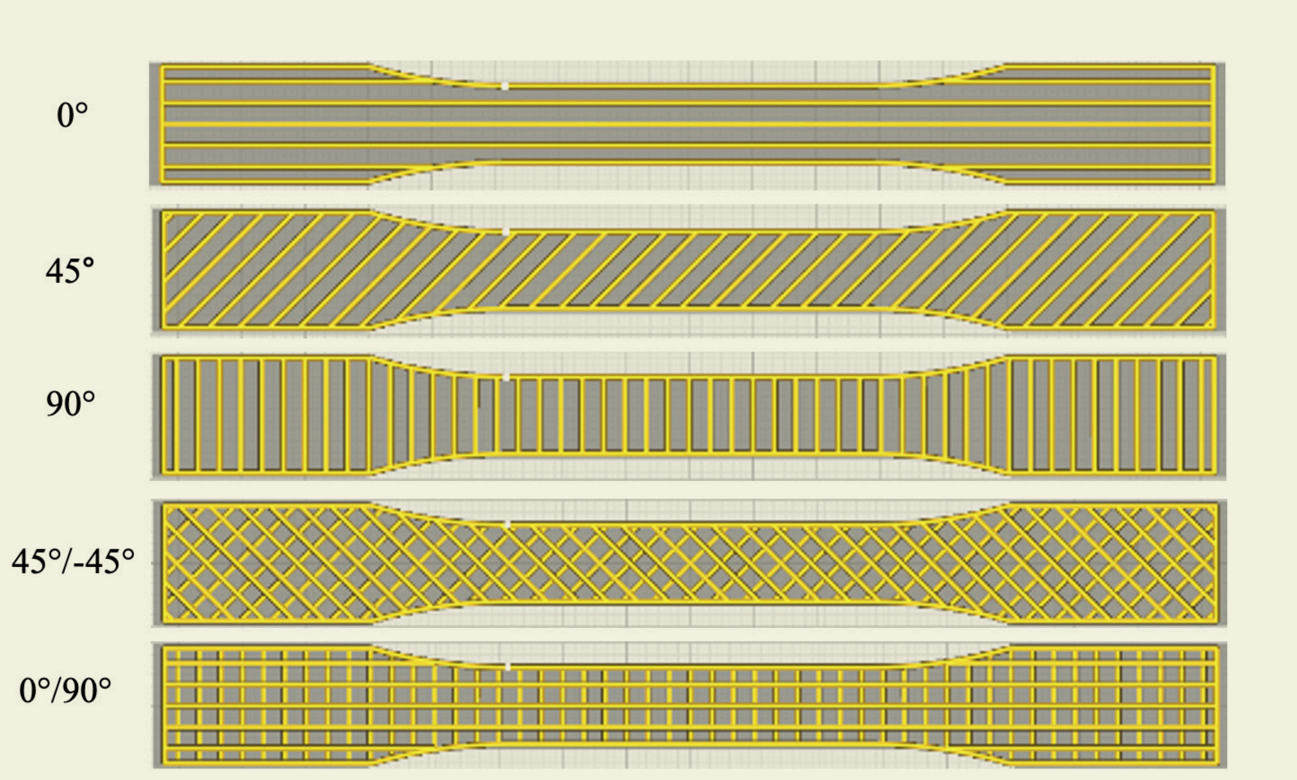

Figure 3. Schematic representation of raster angle variations on standard tensile specimens.

Table 2. Raw results from standard tensile specimens as a result of width (w) and thickness (t) measurements.

Material	Raster Angle	No	w1 (mm)	w2 (mm)	w3 (mm)	t1 (mm)	t2 (mm)	t3 (mm)
PLA	0°	1	13.14	13.15	13.19	3.41	3.45	3.45
		2	13.15	13.21	13.21	3.51	3.49	3.51
		3	13.15	13.15	13.17	3.44	3.50	3.50
	45°	1	13.08	13.01	13.09	3.53	3.53	3.56
		2	13.10	13.12	13.12	3.57	3.57	3.50
		3	13.13	13.14	13.13	3.55	3.58	3.58
	90°	1	13.12	13.12	13.15	3.51	3.53	3.59
		2	13.13	13.13	13.17	3.52	3.51	3.51
		3	13.19	13.10	13.15	3.54	3.55	3.55
	45°/-45°	1	13.19	13.12	13.19	3.49	3.48	3.5
		2	13.14	13.14	13.16	3.45	3.46	3.46
		3	13.07	13.10	13.12	3.49	3.54	3.49
	0°/90°	1	13.18	13.20	13.19	3.56	3.57	3.57
		2	13.13	13.13	13.20	3.47	3.59	3.56
		3	13.11	13.13	13.18	3.55	3.51	3.55
PETG	0°	1	13.19	13.20	13.21	3.50	3.48	3.51
		2	13.26	13.28	13.29	3.48	3.43	3.49
		3	13.24	13.21	13.29	3.48	3.45	3.49
	45°	1	13.20	13.19	13.19	3.51	3.50	3.59
		2	13.21	13.22	13.32	3.56	3.53	3.5
		3	13.23	13.18	13.21	3.50	3.48	3.52
	90°	1	13.22	13.18	13.28	3.53	3.52	3.51
		2	13.26	13.17	13.22	3.48	3.49	3.48
		3	13.24	13.28	13.26	3.34	3.58	3.54
	45°/-45°	1	13.25	13.27	13.24	3.54	3.49	3.52
		2	13.28	13.22	13.29	3.53	3.55	3.55
		3	13.30	13.26	13.32	3.54	3.50	3.51
	0°/90°	1	13.22	13.18	13.19	3.49	3.51	3.51
		2	13.27	13.19	13.20	3.57	3.55	3.54
		3	13.27	13.29	13.29	3.53	3.54	3.53
ABS	0°	1	13.21	13.28	13.30	3.49	3.50	3.49
		2	13.16	13.19	13.20	3.54	3.59	3.50
		3	13.18	13.19	13.20	3.53	3.53	3.56
	45°	1	13.14	13.22	13.16	3.55	3.54	3.54
		2	13.20	13.11	13.18	3.47	3.49	3.50
		3	13.10	13.14	13.13	3.51	3.57	3.49
	90°	1	13.13	13.08	13.08	3.45	3.49	3.48
		2	13.11	13.17	13.11	3.48	3.53	3.46
		3	13.08	13.13	13.10	3.44	3.45	3.43
	45°/-45°	1	13.18	13.17	13.16	3.51	3.55	3.50
		2	13.22	13.15	13.13	3.50	3.57	3.49
		3	13.16	13.13	13.11	3.49	3.50	3.54
	0°/90°	1	13.18	13.13	13.14	3.48	3.47	3.48
		2	13.17	13.12	13.17	3.45	3.47	3.50
		3	13.19	13.14	13.12	3.52	3.53	3.51

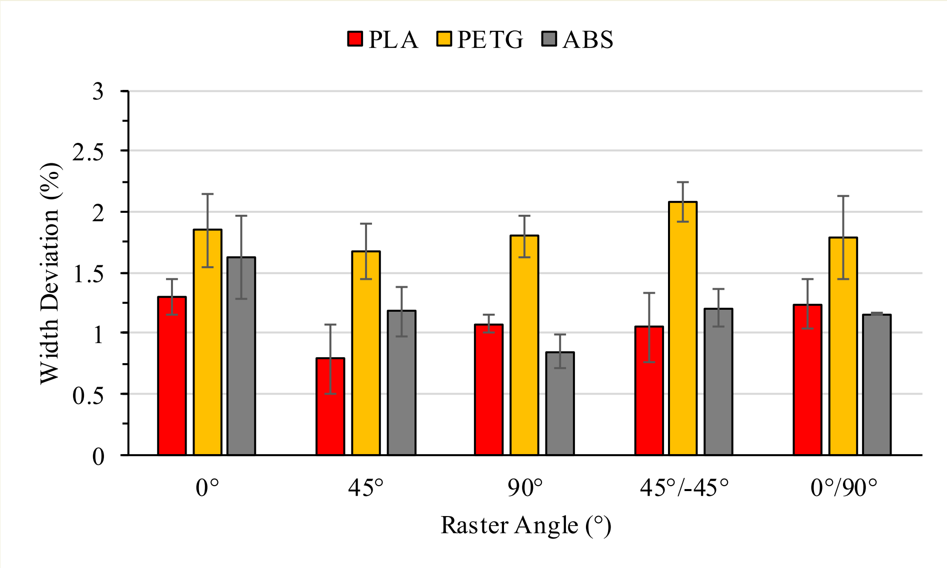

Figure 4. Width deviation (%) with raster angle (°).

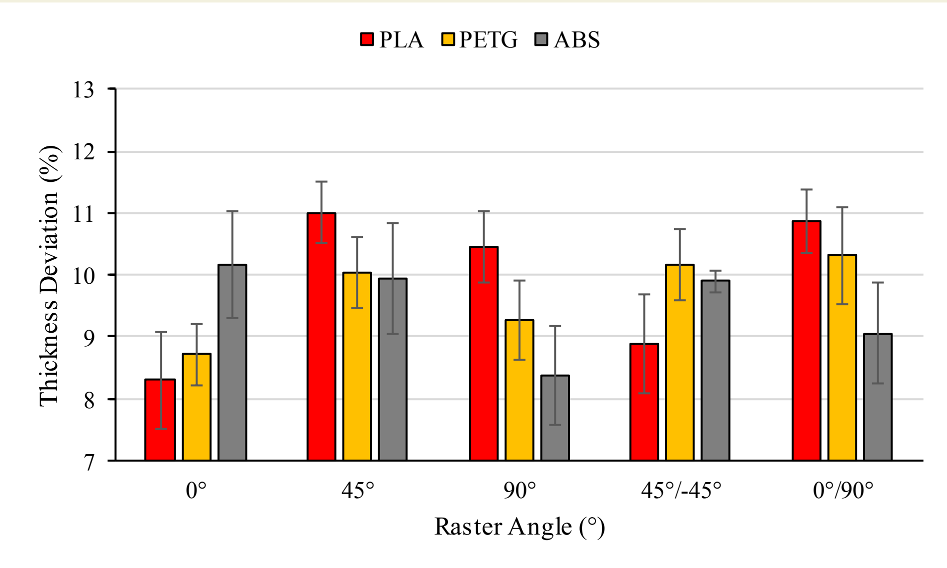

Figure 5. Thickness deviation (%) with raster angle (°).

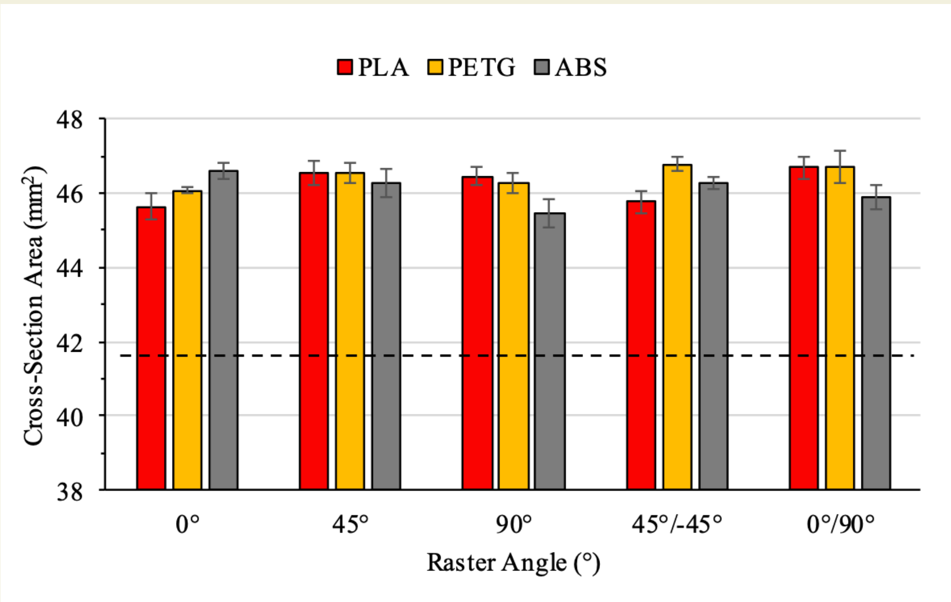

Figure 6. Variation in the cross-section area (theoretical area: 41.6 mm^2) with raster angle (°).

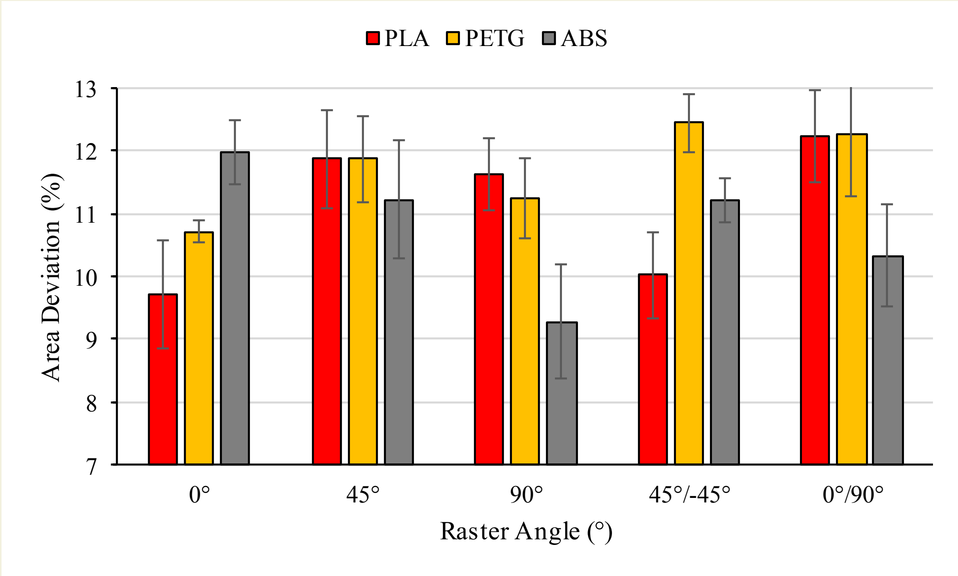

Figure 7. Cross-section area deviation (%) with raster angle (°).

4. Conclusions

In conclusion, the comprehensive analysis of dimensional accuracy in 3D printing, considering different materials (PLA, PETG, and ABS) and raster angles, has provided valuable insights. The following key findings emerge from this study:

- PETG exhibits a higher width deviation than PLA and ABS, indicating differences in dimensional stability. PETG's average width is slightly larger than that of PLA and ABS.
- Raster angle significantly affects width and thickness deviations. Samples with a 90° raster angle generally exhibit lower deviation percentages than 45° or 90° angles. This highlights the importance of selecting an appropriate raster angle for better dimensional accuracy.
- While width deviations remained relatively low (around 2%), thickness deviations were notably higher (around 10%). PETG and PLA show higher levels of thickness deviation, while ABS generally has lower deviations.
- The analysis of cross-sectional areas indicates that, on average, all samples exceed the theoretical area. Percentage deviations in the cross-sectional area generally hover around 11.5 %. PETG at a 45°/-45° raster angle exhibits the largest cross-sectional area, while ABS at a 90° raster angle has the smallest.

In practical terms, understanding the impact of material choice and raster angle on dimensional accuracy is crucial for optimizing 3D printing processes. For applications requiring precise measurements, it is recommended to account for cross-sectional deviations and to calculate the stress based on the actual cross-sectional area rather than the theoretical value to obtain accurate results.

In summary, this study provides valuable data for 3D printing enthusiasts and professionals, offering insights into how material selection and raster angle influence dimensional accuracy. Further research can lead to enhanced printing techniques and improved product quality.

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