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Accuracy Assessment of Micro-Holes in FDM 3D Printing: Influence of Build Orientation and Process Parameters

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Abstract

Fused Deposition Modeling (FDM) has become popular in additive manufacturing; nevertheless, achieving precision in small-scale features, such as micro-holes, is a considerable challenge. This study experimentally examines the impact of critical process factors on the dimensions and geometrical precision of a 0.8 mm diameter hole produced in PLA via an FDM printer. A square specimen (10 mm x 10 mm × 5 mm) including a centrally positioned hole was developed and fabricated using several build orientations (0°, 45°, and 90°), layer heights (0.05, 0.1, and 0.2 mm), printing speeds, and printing temperatures. An experimental strategy utilizing a one-factor-at-a-time methodology was employed, and a profile projector was utilized to assess dimensional deviation and roundness inaccuracy according to the minimum zone circle method. The findings demonstrate that build orientation substantially influences hole precision. Vertical printing (90°) enhances dimensional precision, whereas horizontal printing (0°) improves roundness. Increasing layer height results in increased dimensional inaccuracies while diminishing roundness deviation. Increased printing speeds somewhat increase dimensional inaccuracies while enhancing circularity. The printing temperature minimally impacts dimensional accuracy but enhances roundness at elevated levels. The results offer practical recommendations for optimizing FDM process parameters in the production of small-scale holes and enhance the functional performance of 3D-printed components with micro-features.

Keywords
3D Printing, Dimensional Accuracy, Roundness, Micro features, Micro Holes.

1. Introduction
The 3D printing process involves a variety of techniques that build three-dimensional objects directly from a digital model (CAD Model) by incrementally adding materials in a layer-by-layer style. Also, it's defined as a process of making a physical model from a digital model by adding layers of materials. Many processes and technologies that are working under the umbrella of 3D printing term and all have the same main procedures the difference is only the mechanisms of creating layers. 3D printing technology opened the door to the door for fabrication of very complicated products in different several fields as a rapid prototype, rapid tools, or final products, which were difficult or impossible by conventional technologies. However, 3D printing and especially Fused Deposition Modeling (FDM) technology still suffers from the challenges of producing products that contain small-scale features like holes, Channels, and so on. Many small-featured products cannot be produced by 3D printing due to the limitation of producing small-scale features, like Microfluidic devices with tiny channels and holes, Micro-scale Filters, Air and water gun nozzles, and so on. Even if the 3D printing technology manufactured the small-scale features they will be inaccurate and that affect the functionality of the product. For example, the production of a product (water or air nozzle) with small-scale holes will not be accurate and that will give a non-uniform distribution of water or air exit also affect the flow rate characteristics and pressure, and so on.

Some researchers give attention to investigating the manufacturability and accuracy of 3D printed features, For example, Ameen (2024) found that vertical printing of small holes generally results in better roundness compared to horizontal printing, indicating potential areas for improvement in FDM technology. Also, the limits of minimum manufacturable features (width for square channels, diameter for pins, wall thickness) by FDM process have been identified by Ameen et al. (2024). In other study the key sources of error, including residual stresses causing flatness errors and discrepancies in pin and hole dimensions due to mismatched tool paths and extrusion speeds (Al-Ahmari et al., 2021).

Popescu et al. (2023) examined the variables affecting the repeatability and dimensional precision of 3D-printed holes made using the material extrusion process (MEX). The effect of layer height and printing speed on the geometric correctness of FDM-printed holes made of PETG material was investigated by Alexopoulou et al. (2022). At 20 mm/s, 50 mm/s, and 80 mm/s, they concentrated on holes with sizes of 0.5 mm, 1 mm, 2 mm, 3 mm, and 4 mm, and layer heights of 0.1 mm, 0.2 mm, and 0.3 mm. Zhu et al. (2017) investigated the factors affecting the shrinkage of holes in PLA models made with FDM 3D printing . Sain and Gupta (2022) pointed out that the range of materials available and the mechanical qualities of printed parts frequently limit its applicability. In order to improve the performance and application of FDM technology, the authors point out that more study is essential to extend material alternatives and optimize process parameters. Huttunen (2015) compared fused deposition modeling (FDM) and stereolithography (SLA) to find the effectiveness of 3D printing for small-scale manufacturing and prototyping. Sovetova and Calautit (2024) addressed the high prices and technological constraints that limit additive manufacturing research in the construction industry by concentrating on the creation, calibration, and assessment of a small-scale 3D printer made especially for cement-based materials. Kjar and Huang (2019) examine how micro-scale 3D printing is used in the pharmaceutical industry, emphasizing how technology can revolutionize drug research and delivery. The effects of various process parameters of the accuracy, mechanical and surface characteristics of FDM 3D printing has been examined by Zhou and Han (2021), Wu (2018), Qavi and Rahim (2022), Ćwikła et al. (2017) and Pooladvand, K. (2019). Although several studies have investigated the dimensional accuracy of FDM printed holes, most of them focused on larger hole diameters, different materials, or general dimensional accuracy. Limited attention has been given to micro-holes with diameters below 1 mm, particularly regarding both dimensional deviation and roundness accuracy under different building orientations and process conditions. Therefore, this study investigates the influence of build orientation, layer height, printing speed, and printing temperature on the dimensional and geometrical accuracy of a 0.8 mm micro-hole fabricated using PLA material and FDM technology. The novelty of this work lies in providing an experimental evaluation of micro-hole accuracy using both dimensional deviation and minimum-zone roundness measurements for a feature size that approaches the manufacturability limit of conventional FDM systems.

2. Methodology

To evaluate the effect of process parameters on the accuracy of the printed part, A square specimen with dimensions of 10mm length, 10mm width, and 5mm thickness is designed with a hole of 0.8mm diameter located in the center of the specimen. The designed specimens are fabricated from PLA material using Raise3D E2 3D printer. One factor at time method has been implemented to evaluate the effect of the process parameters on the dimensional and geometrical accuracy of produced holes. Build direction, layer height, print speed and print temperature are considered in this study. Profile projectors have been used to measure the dimensional and geometrical accuracy of produced holes. The dimensional error is determined as the absolute difference between the design dimension and the actual measured dimension, where the roundness has been evaluated using the minimum zone circle.

3. Results and discussion

3.1 Changing the build direction

The test specimens are built in different build directions, 0º, 45º, 90º, relative to the building plate as shown in Figure 1. The other design and process parameters are kept at the default setting.

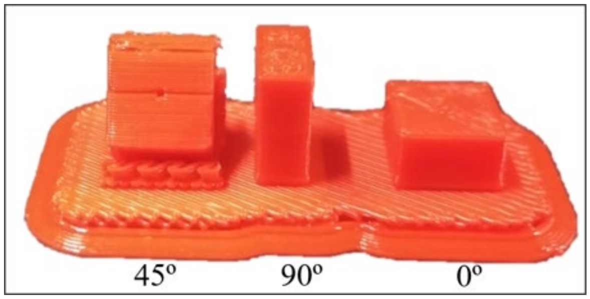


Figure 1. Fabricated specimens in different build directions

Figure 2 shows the holes with different build directions in the profile projector screen.

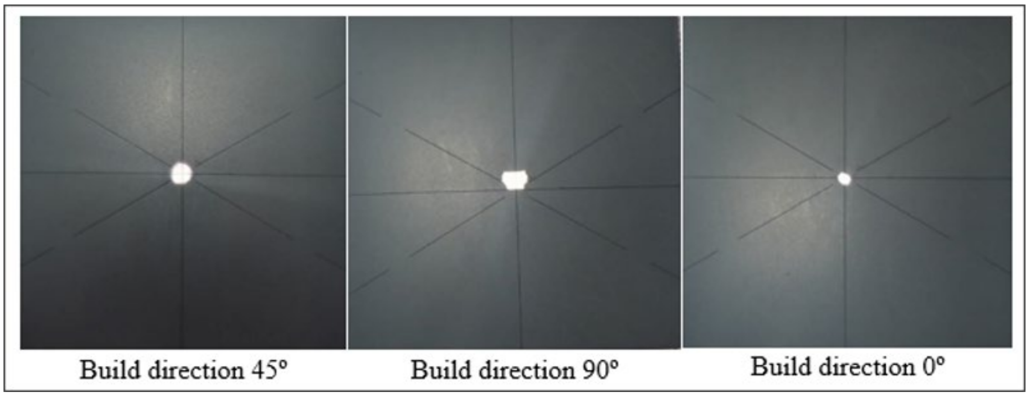


Figure 2. Profile projector images with different build directions.

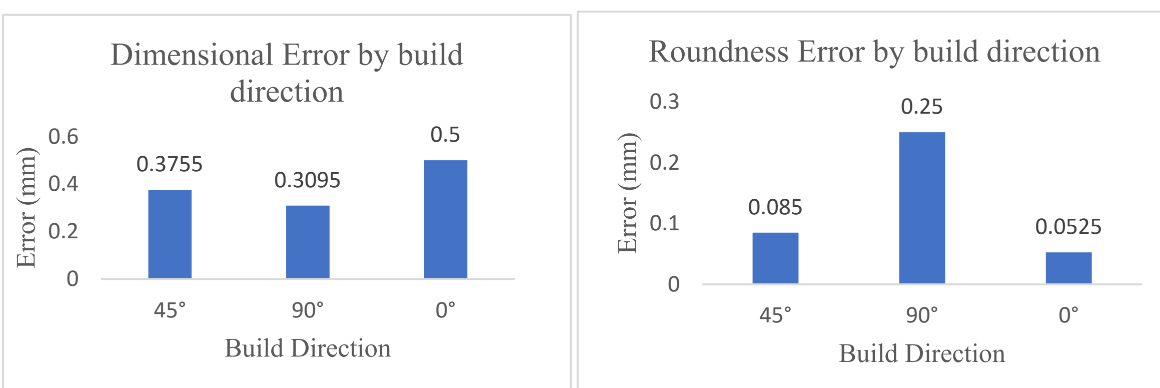


Figure 3. Dimensional error and roundness error with changing of build directions

The results show that the dimensional error is lowest at the 90° build direction (0.3095 mm), indicating better dimensional accuracy in vertical builds. The highest error occurs at 0° (0.5000 mm), where horizontal printing causes more deviation from the intended dimensions. For roundness error, the lowest value appears at 0° (0.0525 mm), meaning horizontally printed parts maintain more circular shapes. The highest roundness error occurs at 90° (0.2500 mm), were vertical layering affects shape precision. In summary, printing vertically (90°) improves dimensional accuracy, while printing horizontally (0°) improves roundness. The 45° direction gives balanced but intermediate results as shown in figure 3. The observed influence of build orientation can be explained by the deposition mechanism of the FDM process. When the hole is printed vertically (90°), the hole boundary is formed layer by layer with reduced unsupported filament deposition, resulting in improved dimensional accuracy. In contrast, horizontally printed holes

(0°) are more susceptible to filament sagging and deformation due to gravity and insufficient support across the hole opening. However, the continuous contour formation in the horizontal orientation contributes to improved roundness compared with the vertically printed holes.

3.2 Changing the layer height

The test specimens are built using different layer heights, 0.05mm, 0.1mm, and 0.2mm. The other design and process parameters are kept at the default setting. Figure 4 shows the results of changing the layer height in different build directions on the dimensional and geometrical accuracy.

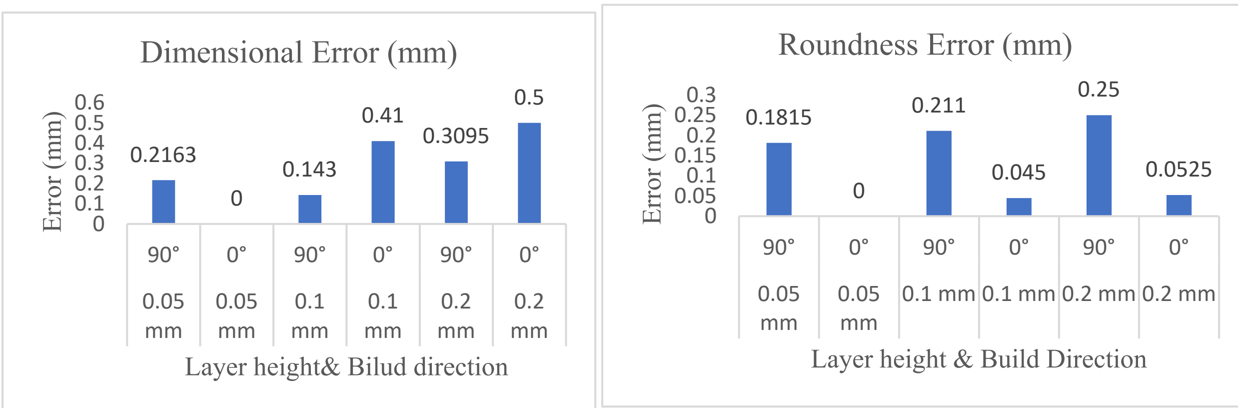


Figure 4. Dimensional error and roundness error with different layer heights

From the results it's clear that the dimensional error increases as the layer height, where the opposite results are found in case of roundness error. The increase in dimensional error with larger layer heights can be attributed to the stair-stepping effect, which becomes more pronounced as layer thickness increases. Thicker layers reduce the ability of the printer to accurately reproduce small geometric details such as micro-holes. On the other hand, the reduced number of deposited layers may decrease local contour irregularities, leading to improved roundness performance. Figure 5 Profile projector images of fabricated holes with different layer heights.

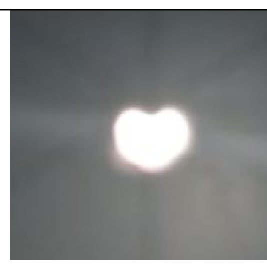
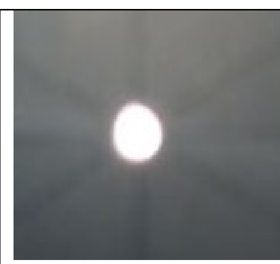
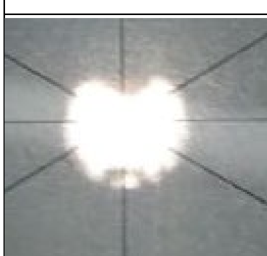
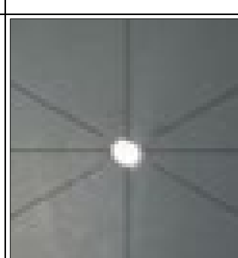
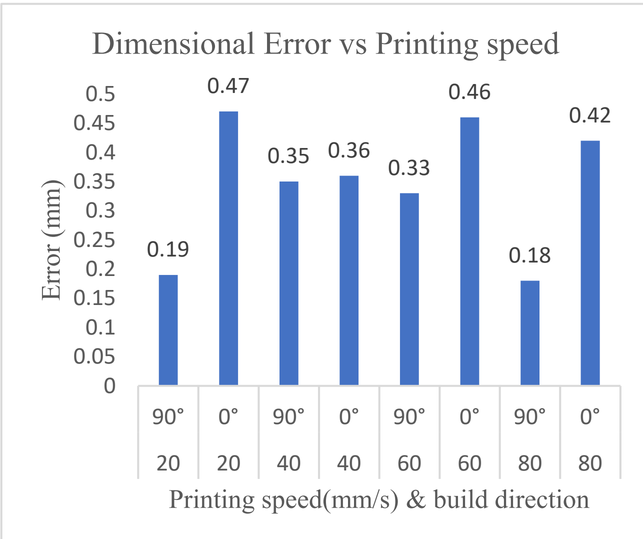
Layer Height 0.05mm and 0º (NA)	 Layer Height 0.05mm and 90º	 Layer Height 0.1mm and 0º
 Layer Height 0.1mm and 90	 Layer Height 0.2mm and 0º	 Layer Height 0.2mm and 90º

Figure 5. Profile projector images with different layer heights

3.3 Changing the printing speed

The test specimens are built using different printing speed, 0.05mm, 0.1mm, and 0.2mm. The other design and process parameters are kept at the default setting. Figure 6 presents the results of changing the printing speed in different build directions on the dimensional and geometrical accuracy.



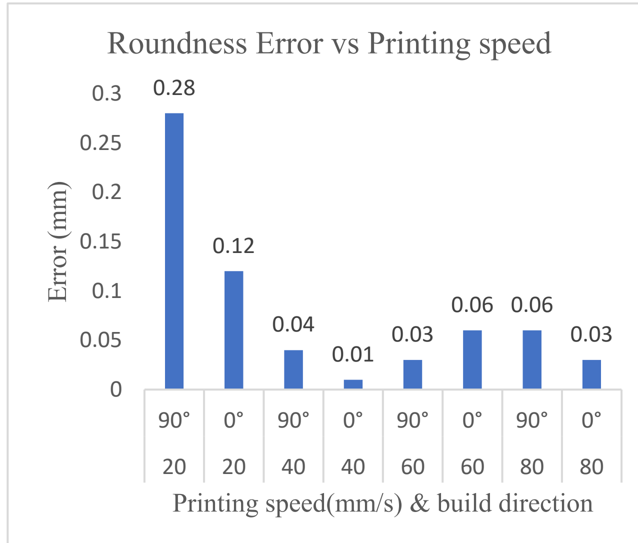
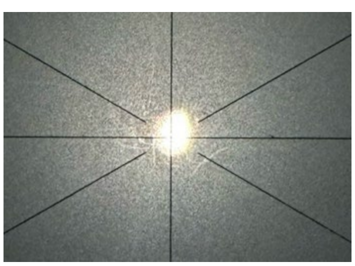
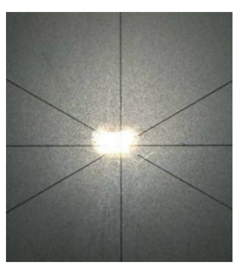
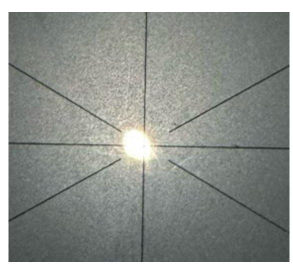
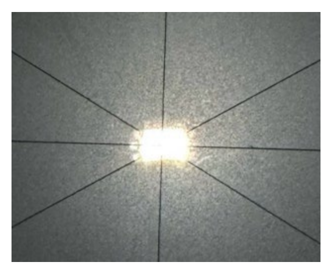


Figure 6. dimensional error and roundness error with different print speeds

The results show that as printing speed increases, dimensional error tends to rise slightly while roundness error decreases. The dimensional deterioration observed at higher printing speeds may be related to reduced deposition control and shorter cooling times, which can lead to slight geometric distortions. Nevertheless, the improved roundness at higher speeds may result from more continuous material flow and reduced localized over-extrusion around the hole perimeter. The 0° build direction generally produces a slightly higher dimensional error compared to the 90° direction, especially at moderate to high speeds, indicating less dimensional accuracy. However, for roundness error, higher speeds improve circular accuracy for both build directions, with differences between them becoming minima. Sample profile projector images are shown in figure 7.

			
Printing speed 20 mm build direction 0°	Printing speed 20 mm build direction 90°	Printing speed 40 mm build direction 0°	Printing speed 40 mm build direction 90°

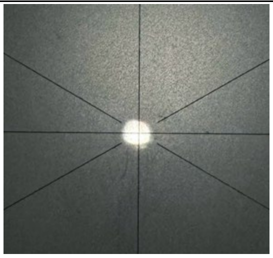
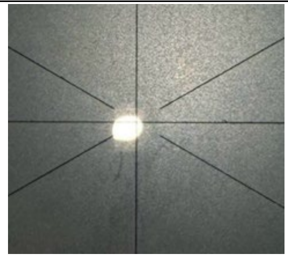
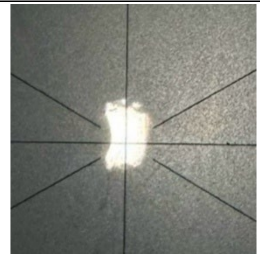
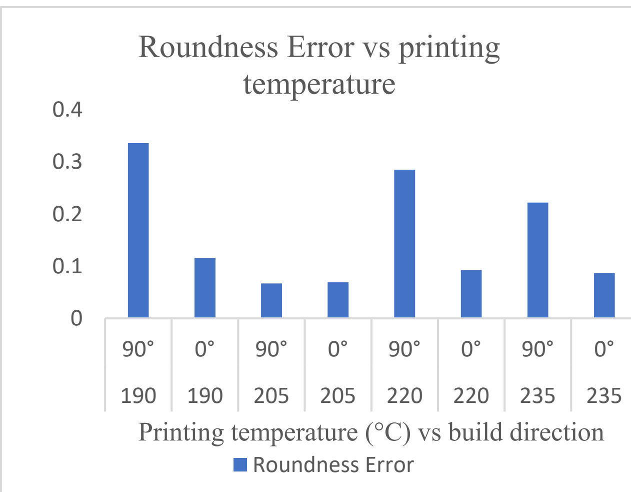
			
Printing speed 60 mm build direction 0°	Printing speed 60 mm build direction 90°	Printing speed 80 mm build direction 0°	Printing speed 80 mm build direction 90°

Figure 7. Sample profile projector images with different print speed

3.4. Changing the printing temperature

In this seection the specimens are built using different printing temperature, 190 °, 205 ° , 220 ° and 235 ° where the other design and process parameters are kept at the default setting. Figure 8 presents the results of changing the printing temperature in different build directions on the dimensional and geometrical accuracy.



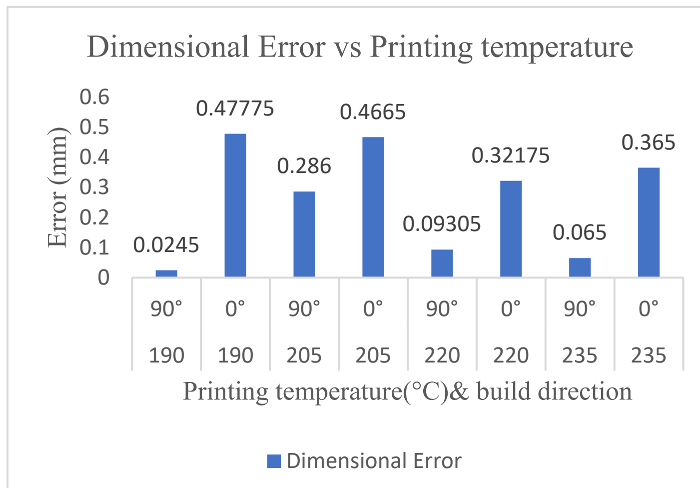


Figure 8. dimensional error and roundness error

The results show that dimensional error fluctuates slightly with temperature but stays higher for the 0° build direction, showing that this orientation tends to produce less accurate dimensions across all temperatures. Meanwhile, roundness error decreases as the printing temperature rises, suggesting improved surface accuracy at higher temperatures. The 90° direction consistently exhibits larger roundness deviations than 0°, especially at lower temperatures. Overall, increasing printing temperature enhances roundness accuracy but has limited impact on dimensional consistency. The improvement in roundness accuracy at elevated temperatures can be explained by the enhanced flowability of molten PLA, which allows smoother contour formation and better fusion between adjacent extruded roads. Since the investigated temperature range remained within the recommended processing window of the material, dimensional accuracy was only marginally affected.

4. Study Limitations

This study has several limitations. Only one hole diameter (0.8 mm) and one material type (PLA) were investigated. Furthermore, the experimental design was based on a one-factor-at-a-time approach. Future studies may consider multiple hole sizes, different materials, and statistically designed experiments to provide a broader understanding of micro-feature manufacturability in FDM printing.

5. Conclusions

This study investigated the effects of build orientation, layer height, printing speed, and printing temperature on the dimensions and roundness precision of a 0.8 mm micro-hole produced via FDM technology. The findings indicate that build orientation is a pivotal factor: the 90° orientation increases dimensional accuracy, whilst the 0° orientation improves roundness. Increasing layer height amplifies dimensional inaccuracies while diminishing roundness divergence. Increased printing speeds somewhat elevate dimensional inaccuracy while enhancing circularity. The printing temperature exhibits no impact on dimensional accuracy, although enhances roundness at elevated levels. These findings offer pragmatic suggestions for the selection of appropriate process parameters in the fabrication of small-scale holes utilizing FDM. The main contribution of this work is the identification of practical process parameter settings for improving the dimensional and geometrical accuracy of micro-holes approaching the manufacturing limits of FDM technology. The findings can support designers and practitioners in selecting suitable printing conditions for functional micro-feature applications.

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