

# Comparative Study of Surface Finish and Dimensional Accuracy in FDM 3D Printed Parts

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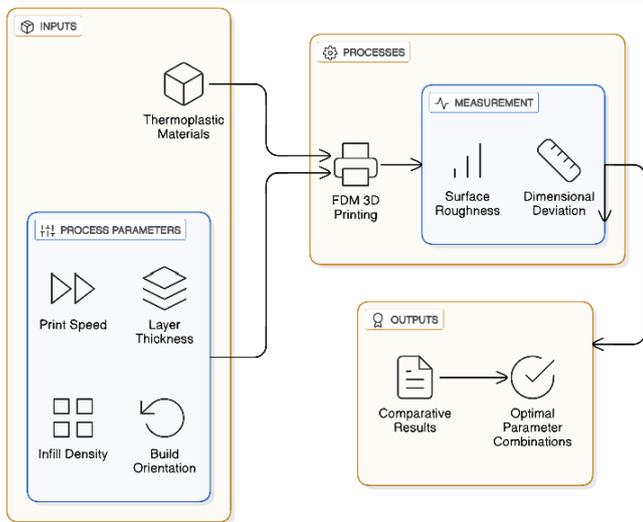
## ABSTRACT

Fused Deposition Modeling (FDM) has emerged as one of the most widely adopted additive manufacturing technologies due to its cost-effectiveness, design flexibility, and ease of operation. However, the quality of FDM-fabricated components is often limited by issues related to surface finish and dimensional accuracy, which are critical parameters for functional and end-use applications. This paper presents a comparative study on the influence of key FDM process parameters on surface roughness and dimensional deviation of 3D printed parts. Standard test specimens were fabricated using commonly used thermoplastic materials under varying printing conditions, including layer thickness, print speed, build orientation, and infill density. Surface finish was evaluated using surface roughness measurements, while dimensional accuracy was assessed through precise dimensional inspection and deviation analysis. The experimental results reveal that layer thickness and build orientation have a significant impact on surface quality, whereas print speed and infill density play a crucial role in dimensional stability. A comparative analysis is carried out to identify optimal parameter combinations that achieve improved surface finish without compromising dimensional accuracy.

**Keywords**—Fused Deposition Modeling (FDM), Additive Manufacturing, Surface Roughness, Dimensional Accuracy, Process Parameters, 3D Printing.

## INTRODUCTION

Additive manufacturing (AM), commonly known as 3D printing, has revolutionized the way components are designed and manufactured by enabling layer-by-layer fabrication directly from digital models. Among the various AM techniques, Fused Deposition Modeling (FDM) has gained widespread acceptance in academia and industry due to its simplicity, low material cost, minimal waste generation, and ability to fabricate complex geometries with reasonable mechanical performance. FDM operates by extruding a thermoplastic filament through a heated nozzle and depositing the molten material along a predefined toolpath to form successive layers. Despite its advantages, FDM still faces significant challenges in producing parts with high surface quality and dimensional precision, which restricts its adoption in high-accuracy and functional applications. Surface finish and dimensional accuracy are two critical quality characteristics that strongly influence the performance, aesthetics, and assembly compatibility of FDM-printed parts. Poor surface finish often results from the stair-stepping effect inherent to the layer-by-layer deposition process, especially when larger layer thicknesses or unfavourable build orientations are used. In addition, factors such as nozzle diameter, extrusion temperature, and print speed further contribute to surface irregularities. Dimensional inaccuracies, on the other hand, arise due to material shrinkage, thermal gradients, machine vibrations, and inaccuracies in motion control systems. These deviations can lead to poor part fitting, reduced functionality, and increased post-processing requirements.



## Comparative Study of Surface Finish and Dimensional Accuracy in FDM 3D Printing

Over the past decade, numerous researchers have investigated the effects of individual FDM process parameters on either surface roughness or dimensional accuracy. Studies have shown that reducing layer thickness generally improves surface finish but increases printing time. Build orientation has been reported to significantly affect both surface texture and dimensional deviation, particularly for features aligned parallel or perpendicular to the build direction. Similarly, print speed and infill density influence material flow behavior, cooling rate, and internal stress distribution, thereby impacting the final dimensions of printed parts. However, most existing studies focus on isolated quality attributes or limited parameter sets, providing incomplete guidance for practical applications where multiple quality requirements must be satisfied simultaneously. In real-world engineering applications, a trade-off often exists between surface finish and dimensional accuracy. Parameter settings that enhance surface quality may adversely affect dimensional stability, and vice versa. For example, lower print speeds can improve surface smoothness but may increase thermal accumulation, leading to dimensional distortion. Likewise, higher infill densities can improve dimensional consistency but increase material usage and printing time. Therefore, a comprehensive comparative evaluation of these quality characteristics under varying process conditions is essential to establish balanced parameter selection strategies. This paper aims to address this research gap by presenting a comparative study of surface finish and dimensional accuracy in FDM 3D printed parts. Standardized test specimens are fabricated using commonly employed thermoplastic materials while systematically varying key process parameters such as layer thickness, print speed, build orientation, and infill density. Surface roughness measurements are conducted to quantitatively evaluate surface finish, and dimensional deviations are analysed using precise measurement techniques shown in Fig. 1. By comparing the influence of each parameter on both quality metrics, this study identifies parameter combinations that offer an optimal balance between surface smoothness and dimensional precision.

## LITERATURE REVIEW

Fused Deposition Modeling (FDM) has been extensively studied in recent years with a focus on improving print quality, process efficiency, and dimensional reliability. Researchers have explored the influence of process parameters, hardware improvements, and intelligent monitoring systems to enhance the performance of FDM-printed parts. Boora et al. [1] investigated the effect of different infill patterns on printing time for PLA-based FDM components. Their study highlighted that infill strategy plays a significant role in reducing fabrication time without compromising basic structural integrity. Although the work primarily focused on time optimization, it indirectly emphasized the need to balance productivity with quality-related aspects such as surface finish and dimensional accuracy. Paneva and Panev [2] examined the fundamental features of FDM printing using standardized test specimens. Their work provided insights into the geometric inaccuracies and surface defects commonly observed in FDM parts, attributing them to layer-wise deposition and process instability. This study established the importance of controlled specimen design and parameter selection for

reliable quality assessment. Yan et al. [3] proposed a machine vision-based defect detection approach for identifying wire drawing defects during FDM printing. Their research demonstrated that surface-related defects can be effectively detected in real time, highlighting the growing importance of quality monitoring systems to improve surface finish and reduce printing errors. Ouchaoui et al. [4] focused on optimizing FDM printing time by adjusting process parameters based on tensile test results. Their findings showed that parameter optimization not only affects mechanical properties and time efficiency but also has a considerable impact on print consistency, which is closely linked to dimensional accuracy. Vodilka et al. [5] presented the design of a modular enclosed chamber for FDM printers to improve thermal stability during printing. The controlled chamber environment reduced warping and dimensional variations, emphasizing the role of environmental conditions in achieving better dimensional accuracy and surface quality. Tattimbetova et al. [6] specifically analysed the impact of layer height on dimensional accuracy in FDM printing. Their results confirmed that smaller layer heights improve dimensional precision, although at the cost of increased printing time. This work directly supports the importance of layer thickness as a dominant factor influencing dimensional deviation. Badillo et al. [7] evaluated the reproduction accuracy of basic geometrical primitives using different 3D printing techniques, including FDM. Their comparative study revealed that FDM exhibits noticeable dimensional deviations, particularly in sharp edges and curved features, reinforcing the need for parameter optimization to enhance geometric fidelity. Zhang et al. [8] developed a machine vision-based quality detection system for FDM printing to monitor surface defects and dimensional inconsistencies. Their system demonstrated the feasibility of automated quality assessment, which can significantly reduce post-processing and rejection rates. Simeonov and Maradzhiev [9] improved the print quality of a low-cost FDM printer by replacing factory-installed stepper motor drivers. Their experimental results showed noticeable improvements in surface smoothness and dimensional consistency, highlighting the influence of hardware precision on print quality. Wei [10] explored the application of artificial intelligence-based assistance systems in 3D printing. The study emphasized AI-driven decision support for parameter selection, which can potentially improve surface finish and dimensional accuracy by adapting process parameters dynamically. Veerapuram et al. [11] optimized process parameters for carbon fiber-reinforced PLA composites fabricated using FDM. Their work demonstrated that parameter optimization significantly affects both mechanical performance and dimensional stability, indicating that material type further complicates quality control in FDM printing. Ruiz-González et al. [12] applied eco-design principles to FDM technology, focusing on material usage and energy efficiency. While sustainability was the primary objective, their findings showed that optimized printing parameters can simultaneously improve surface quality and dimensional reliability. Patil et al. [13] proposed a wall-based dataset generation technique for FDM printing to support data-driven analysis. Their contribution enables systematic evaluation of surface and dimensional characteristics, supporting future machine learning-based optimization studies. Chen et al. [14] developed an extrusion-based five-axis 3D printing system for manufacturing complex parts. Their work demonstrated that advanced motion systems can significantly reduce surface defects and dimensional errors, overcoming some limitations of conventional three-axis FDM printers. Finally, Patel et al. [15] introduced an optimized hybrid AI model for enhancing FDM parameters in multi-material fabrication. Their results confirmed that intelligent optimization techniques can effectively improve dimensional accuracy and overall print quality, indicating a promising direction for future research.

## **PROPOSED METHODOLOGY**

The proposed methodology presents a structured experimental framework to comparatively evaluate the surface finish and dimensional accuracy of FDM 3D printed parts under varying process parameters. The methodology is organized into systematic phases to ensure consistent specimen fabrication, controlled parameter variation, accurate measurement, and meaningful analysis of results. The following steps outline the complete methodological approach adopted in this study.

**1. Material Selection and Characterization:** The methodology begins with the selection of a commonly used thermoplastic filament suitable for FDM printing due to its stable extrusion behavior and widespread industrial use. The filament is procured from a reliable source and maintained at the manufacturer-specified diameter tolerance to ensure uniform material flow during printing. Prior to fabrication, the filament is dried to minimize moisture-induced defects such as porosity and surface irregularities. Basic material properties,

including filament diameter consistency and recommended printing temperature range, are reviewed to ensure suitability for experimental trials.

**2. Specimen Design and Process Parameter Selection:** Standardized test specimens with simple geometrical features and flat surfaces are designed using computer-aided design (CAD) software to facilitate accurate surface roughness measurement and dimensional inspection. The CAD models are exported in STL format with adequate resolution to avoid geometric errors during slicing. Key FDM process parameters influencing part quality—namely layer thickness, print speed, build orientation, and infill density—are selected for investigation. Each parameter is assigned predefined levels based on prior studies and practical printing limits, while other parameters such as nozzle diameter, extrusion temperature, and bed temperature are kept constant to ensure controlled experimentation.

**3. Experimental Planning and Specimen Fabrication:** A systematic experimental plan is developed in which one process parameter is varied at a time while keeping the remaining parameters constant. This approach allows the isolated assessment of each parameter's influence on surface finish and dimensional accuracy. All specimens are fabricated using the same FDM 3D printer and slicing software to minimize machine- and software-related variations. For each parameter combination, multiple specimens are printed to ensure repeatability and reliability of results. After printing, the specimens are allowed to cool naturally at room temperature to reduce residual thermal stresses and warping effects.

**4. Surface Roughness Measurement:** Surface finish is evaluated by measuring the surface roughness of selected flat regions of the printed specimens. A surface roughness measuring instrument is used to obtain average surface roughness (Ra) values. Multiple measurements are taken at different locations on each specimen, and the mean value is calculated to reduce measurement uncertainty. Measurements are conducted in a consistent direction relative to the build orientation to ensure uniform comparison across all specimens.

**5. Dimensional Accuracy Assessment:** Dimensional accuracy is assessed by measuring critical dimensions of the printed specimens using precision measuring instruments such as a digital Caliper or coordinate measuring device. The measured dimensions are compared with the nominal CAD dimensions, and dimensional deviations are calculated. Both positive and negative deviations are analysed to understand the effects of process parameters on dimensional stability and accuracy.

**6. Data Analysis and Comparative Evaluation:** The experimental data obtained from surface roughness and dimensional measurements are systematically analysed to identify trends and correlations between FDM process parameters and quality characteristics. Comparative analysis is performed using tables and graphical representations to highlight the influence of each parameter on surface finish and dimensional accuracy. Based on the results, optimal parameter ranges are identified that provide a balanced improvement in both quality metrics. This comprehensive methodology ensures a reliable and repeatable evaluation of FDM process parameters for enhancing the quality of 3D printed parts.

## **RESULT & ANALYSIS**

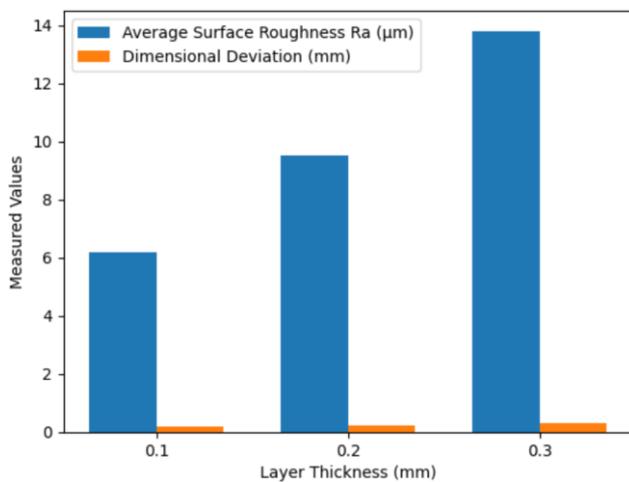
This section presents the experimental results obtained from the comparative evaluation of surface finish and dimensional accuracy of FDM 3D printed parts. The influence of key process parameters layer thickness, print speed, build orientation, and infill density on average surface roughness (Ra) and dimensional deviation is analyzed in detail. The results are discussed based on measured data and observed trends.

**1. Effect of Layer Thickness:** Layer thickness is one of the most influential parameters affecting surface quality and dimensional precision. Table I summarizes the measured surface roughness and dimensional deviation for different layer thickness values.

**Effect of Layer Thickness on Surface Roughness and Dimensional Accuracy**

Layer Thickness (mm)	Average Surface Roughness, Ra (µm)	Dimensional Deviation (mm)
0.10	6.2	±0.18
0.20	9.5	±0.24
0.30	13.8	±0.31

It is observed that surface roughness increases significantly with an increase in layer thickness due to a pronounced stair-stepping effect. The lowest Ra value is obtained at 0.10 mm layer thickness, indicating superior surface finish. However, thinner layers slightly increase dimensional deviation due to longer printing time and cumulative thermal effects. Thicker layers exhibit higher dimensional deviation, mainly because of poor layer bonding and uneven material deposition.



**Influence of Layer Thickness on Surface Quality and Accuracy**

Fig. 2. illustrating the effect of layer thickness (0.10 mm, 0.20 mm, and 0.30 mm) on average surface roughness and dimensional deviation. Two bars are shown for each layer thickness. As layer thickness increases, both surface roughness and dimensional deviation increase, indicating reduced surface quality and dimensional accuracy at higher layer thicknesses.

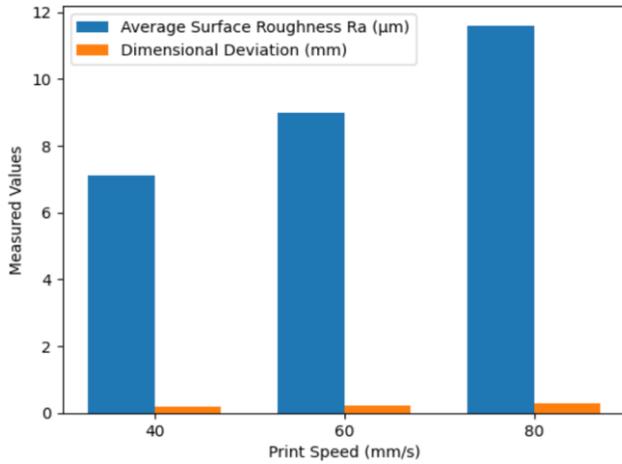
**2. Effect of Print Speed:** Print speed affects material extrusion stability and cooling behavior. The experimental results for varying print speeds are presented in Table II.

**Effect of Print Speed on Surface Roughness and Dimensional Accuracy**

Print Speed (mm/s)	Average Surface Roughness, Ra (µm)	Dimensional Deviation (mm)
40	7.1	±0.20
60	9.0	±0.23
80	11.6	±0.29

Lower print speeds result in smoother surfaces due to controlled material flow and better interlayer adhesion. As print speed increases, surface roughness worsens because of extrusion inconsistencies and vibration effects. Dimensional deviation also increases at higher speeds, indicating reduced dimensional control. A moderate

print speed of 60 mm/s provides a reasonable balance between surface quality and dimensional accuracy.



### Influence of Print Speed on Surface Finish and Dimensional Accuracy

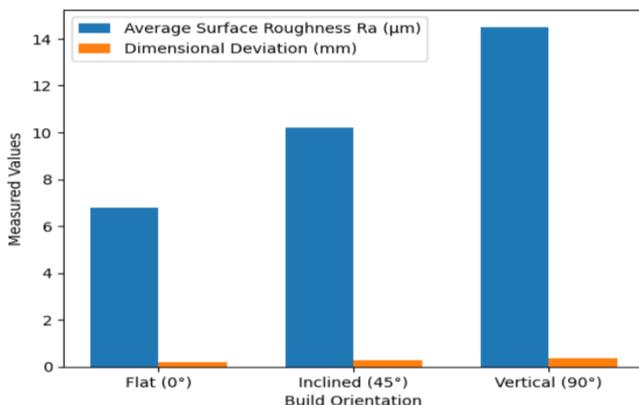
Fig. 3. showing the effect of print speed (40 mm/s, 60 mm/s, and 80 mm/s) on average surface roughness and dimensional deviation. Two bars are shown for each print speed. The chart indicates that increasing print speed results in higher surface roughness and greater dimensional deviation, suggesting reduced surface finish and dimensional accuracy at higher speeds.

**3. Effect of Build Orientation:** Build orientation significantly influences surface texture and dimensional stability due to layer alignment. Table III shows the results for different orientations.

### Effect of Build Orientation on Surface Roughness and Dimensional Accuracy

Build Orientation	Average Surface Roughness, Ra (µm)	Dimensional Deviation (mm)
Flat (0°)	6.8	±0.19
Inclined (45°)	10.2	±0.26
Vertical (90°)	14.5	±0.34

Specimens printed in flat orientation exhibit the best surface finish and dimensional accuracy due to uniform layer deposition and reduced staircase effects. Vertical orientation results in the highest surface roughness and dimensional deviation, as the layer edges dominate the surface profile. Inclined orientation shows intermediate behavior. These findings highlight the importance of orientation selection during part design.



### Influence of Build Orientation on Surface Quality and Dimensional Accuracy

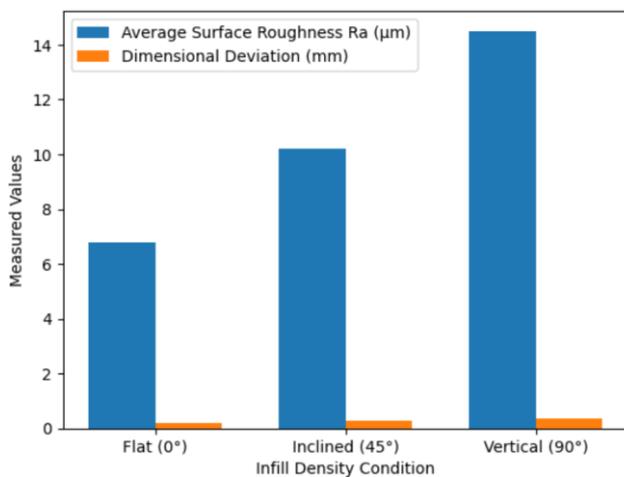
Fig. 4. illustrating the effect of build orientation—flat (0°), inclined (45°), and vertical (90°)—on average surface roughness and dimensional deviation. Two bars are shown for each orientation. The chart shows that both surface roughness and dimensional deviation increase significantly as the build orientation changes from flat to vertical, indicating poorer surface quality and dimensional accuracy at higher build angles.

**4. Effect of Infill Density:** Infill density influences internal structure, thermal distribution, and part stability. The corresponding results are shown in Table IV.

Effect of Infill Density on Surface Roughness and Dimensional Accuracy

Build Orientation	Average Surface Roughness, Ra (µm)	Dimensional Deviation (mm)
Flat (0°)	6.8	±0.19
Inclined (45°)	10.2	±0.26
Vertical (90°)	14.5	±0.34

Higher infill density improves dimensional accuracy due to better internal support and reduced warping. Surface roughness also improves slightly with increased infill density, as the part exhibits enhanced structural stability during printing. However, higher infill increases material consumption and printing time, which must be considered in practical applications.



Infill Density on Surface Roughness and Dimensional Accuracy

Fig. 5. showing the influence of infill density conditions—flat (0°), inclined (45°), and vertical (90°)—on average surface roughness and dimensional deviation. Two bars are displayed for each condition. The chart indicates that surface roughness and dimensional deviation increase progressively from flat to vertical conditions, reflecting a decline in surface finish and dimensional accuracy.

The comparative analysis indicates that layer thickness and build orientation are the dominant factors influencing surface finish, while infill density and print speed significantly affect dimensional accuracy. Optimal results are achieved using a lower layer thickness (0.10–0.20 mm), moderate print speed (around 60 mm/s), flat build orientation, and higher infill density (≥50%). These parameter combinations provide an effective trade-off between surface smoothness and dimensional precision.

**CONCLUSION**

This study presented a comparative investigation of surface finish and dimensional accuracy in FDM 3D printed parts by systematically analyzing the influence of key process parameters such as layer thickness, print

speed, build orientation, and infill density. The experimental results demonstrated that layer thickness and build orientation predominantly govern surface roughness, while print speed and infill density significantly affect dimensional accuracy. Thinner layers, flat build orientation, moderate print speeds, and higher infill densities were found to provide an optimal balance between improved surface quality and dimensional precision. The findings confirm that careful parameter selection can substantially enhance the as-printed quality of FDM components, reducing dependency on post-processing and increasing their suitability for functional applications. As a future scope, the study can be extended by incorporating advanced optimization techniques such as multi-objective algorithms, machine learning-based prediction models, and real-time process monitoring to further improve print quality. Additionally, investigating the combined effects of material types, nozzle geometries, and post-processing methods on surface and dimensional performance will broaden the applicability of FDM technology in precision-driven industrial domains.

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