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Optimization of Print Quality and Mechanical Strength in Additive Manufacturing Using Different Nozzle Diameters

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Abstract: Additive Manufacturing (AM) has emerged as a transformative fabrication technology enabling rapid prototyping and custom production of complex geometries. Among various AM processes, Fused Deposition Modeling (FDM) remains the most widely adopted due to its simplicity, cost-effectiveness, and material versatility. However, achieving an optimal balance between print quality and mechanical performance continues to be a major challenge. This research investigates the influence of different nozzle diameters (0.2 mm, 0.4 mm, 0.6 mm) on the mechanical strength and surface quality of 3D-printed PLA components. Standardized tensile specimens were fabricated under controlled conditions, with constant parameters such as infill density, layer height, and printing speed. Tensile testing, surface roughness measurement, and dimensional accuracy evaluations were conducted. Statistical modeling using Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) was applied to optimize parameters. Results indicate that smaller nozzles yield superior surface quality, while larger nozzles enhance interlayer adhesion and tensile strength. The optimal trade-off was found at a 0.4 mm nozzle diameter, achieving high strength and acceptable print quality. This study provides practical insights for additive manufacturing users seeking to optimize process performance.

Keywords: *Additive Manufacturing, Fused Deposition Modeling, Nozzle Diameter, Surface Roughness, Tensile Strength, Optimization, Response Surface Methodology, PLA.*

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I. INTRODUCTION

Additive Manufacturing (AM), popularly known as 3D printing, represents a paradigm shift from traditional subtractive methods to layer-by-layer fabrication. It allows designers to produce parts directly from computer-aided design (CAD) data without tooling or molds. Among AM techniques, Fused Deposition Modeling (FDM) has become the most accessible and economical. It extrudes thermoplastic filament through a heated nozzle to build parts layer by layer.[1-3]

However, printed parts' performance depends heavily on several process parameters, such as layer thickness, nozzle temperature, infill density, print speed, raster orientation, and nozzle diameter. Each parameter affects the quality, strength, and dimensional accuracy of the printed part. Among these, nozzle diameter plays a dual role: it determines both extrusion rate and deposition width, influencing the trade-off between surface resolution and interlayer bonding.[4-6]

A smaller nozzle (e.g., 0.2 mm) enhances print precision and surface smoothness but increases print time and may cause weak bonding between layers. Conversely, larger nozzles (e.g., 0.6 mm) improve mechanical strength by providing thicker extrusions but compromise detail and finish. Thus, determining an optimal nozzle size for the best balance between aesthetics and performance is critical.

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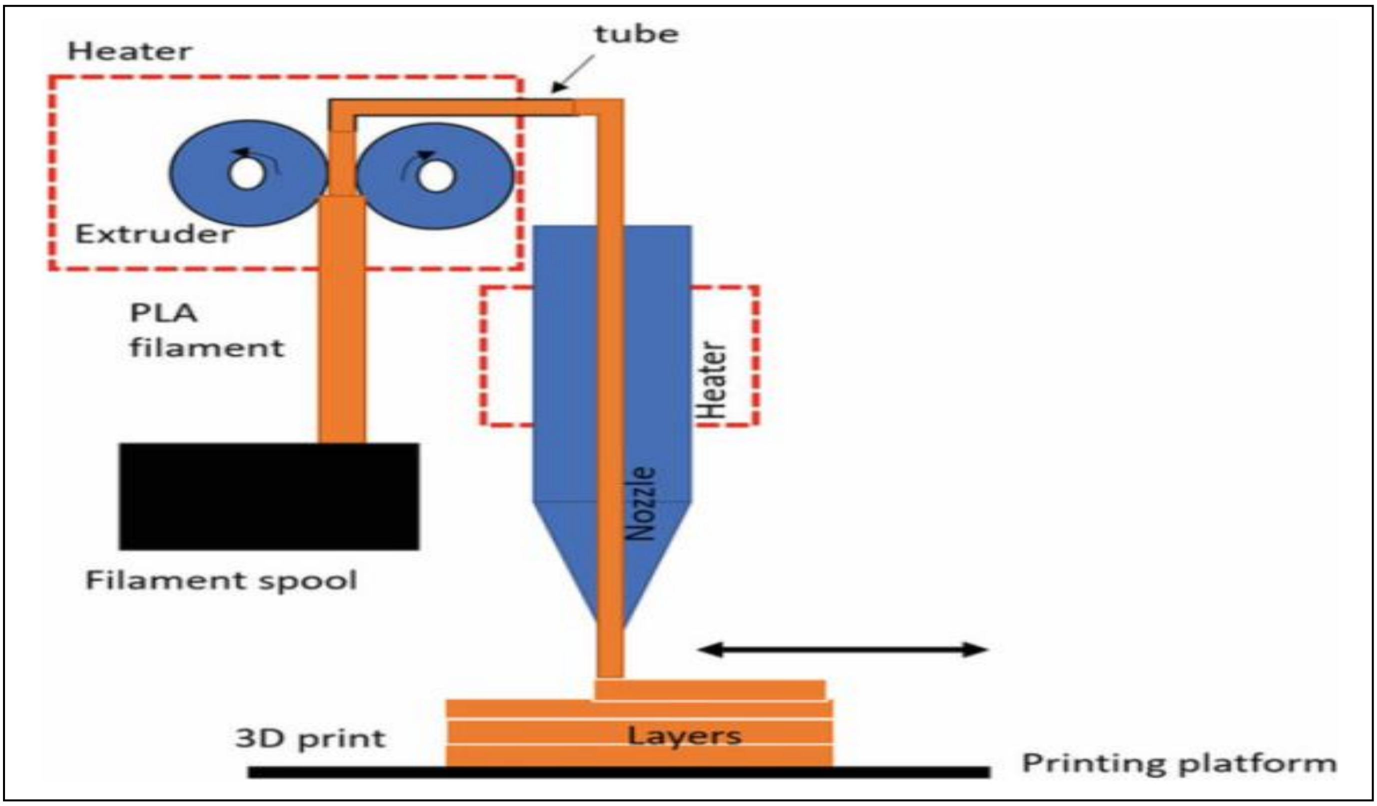

Fig 1 Fused Deposition Modeling (FDM)
(Image Courtesy: Researchgate.Net)

This study investigates the effect of nozzle diameter on the print quality and mechanical strength of FDM-printed PLA parts. Statistical models are used to identify the optimal configuration for superior mechanical and surface characteristics.[7-11]

II. LITERATURE REVIEW

Numerous studies have explored the impact of FDM process parameters on printed part performance. Sood et al. (2010) established regression models correlating layer thickness, orientation, and infill with tensile strength. Mohamed et al. (2016) highlighted that extrusion temperature and layer height strongly influence surface roughness. Ziemian and Crawn (2012) demonstrated anisotropic behavior in FDM parts due to raster orientation.[12]

Nozzle diameter has received relatively less focused attention compared to other parameters. Zhang et al. (2018) showed that smaller nozzles improved dimensional accuracy but prolonged print duration. Singh and Bedi (2019) observed that larger nozzle diameters resulted in enhanced interlayer fusion, thereby improving tensile and flexural strength. Kalita and Kumar (2021) applied multi-objective optimization to FDM parameters and concluded that mechanical properties and print quality must be optimized simultaneously using RSM.[13-19]

Despite these efforts, there remains a lack of integrated studies addressing the joint optimization of surface and mechanical performance with nozzle diameter variation under fixed process conditions. The present work aims to fill this gap by combining experimental investigation and statistical modeling to identify the optimal nozzle diameter.[14, 20, 21]

III. EXPERIMENTAL METHODOLOGY

➢ *Material Selection*

Polylactic Acid (PLA) filament was chosen due to its biodegradability, dimensional stability, and popularity in FDM. The filament diameter was maintained at 1.75 mm with ±0.02 mm tolerance.[22, 23]

➢ *Equipment Used*

A Creality Ender-3 Pro 3D printer equipped with interchangeable brass nozzles (0.2 mm, 0.4 mm, 0.6 mm) was used. The printer operated using G-code generated from Ultimaker Cura software.[24-26]

➢ *Process Parameters*

Except for nozzle diameter, all other printing parameters were kept constant to isolate its effect.

Table 1 Process Parameters

Parameter	Value
Layer height	0.2 mm

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Infill density	100%
Print speed	50 mm/s
Nozzle temperature	200 °C
Bed temperature	60 °C
Raster angle	45°
Material	PLA

➢ *Specimen Design*

Tensile specimens were printed following ASTM D638 Type IV standard geometry. Five samples were printed for each nozzle size to ensure repeatability. Each specimen was allowed to condition for 24 h at 23 °C and 50% relative humidity before testing.[27-31]

IV. TESTING AND MEASUREMENT

➢ *Tensile Strength*

Testing was performed using a Universal Testing Machine (UTM) with a 10 kN load cell at a crosshead speed of 5 mm/min. Ultimate tensile strength (UTS) was calculated as:

$$\sigma = F_{max} / A$$

Where $F_{max}$is the maximum load and A is the cross-sectional area.

➢ *Surface Roughness*

Surface roughness (Ra) was measured using a Mitutoyo SJ-210 profilometer over three different regions per sample, with mean values recorded.

➢ *Dimensional Accuracy*

The printed specimens' dimensions were compared to CAD model dimensions using a digital vernier caliper with 0.01 mm resolution. Dimensional deviation was expressed as:

$$\text{Deviation} = \frac{[D_{printed} - D_{model}]}{D_{model}} \times 100$$

V. RESULTS

➢ *Surface Quality*

The smallest nozzle (0.2 mm) produced smooth surfaces with minimal visible layer lines. The average Ra value was 4.3 µm, whereas 0.4 mm and 0.6 mm nozzles yielded Ra values of 6.8 µm and 11.2 µm, respectively. Smaller extrusion widths reduced surface waviness, enhancing print quality.

➢ *Tensile Strength*

The mean tensile strengths obtained were:

- 0.2 mm nozzle: 48.5 MPa
- 0.4 mm nozzle: 54.1 MPa
- 0.6 mm nozzle: 57.3 MPa

Strength increased with nozzle size due to improved interlayer contact and polymer chain diffusion.

➢ *Dimensional Accuracy*

The 0.2 mm nozzle exhibited the lowest dimensional deviation (0.32%), while 0.6 mm showed higher deviation (0.89%). Larger bead deposition caused over-extrusion effects and rounding of sharp edges.

VI. STATISTICAL ANALYSIS

➢ *Response Surface Methodology (RSM)*

RSM was applied to model and optimize the relationship between nozzle diameter (A), print speed (B), and temperature (C) on tensile strength (Y_1) and surface roughness (Y_2). The regression models obtained were:

$$Y_1 = 45.2 + 6.8A + 1.2B + 0.9C - 0.3AB - 0.5A^2$$

➢ *ANOVA Results*

ANOVA confirmed that nozzle diameter was the most significant factor ($p < 0.001$) affecting both responses. The model's R^2 values were 0.97 for tensile strength and 0.95 for surface roughness, indicating excellent correlation between experimental and predicted results.[32-35]

VII. DISCUSSION

➢ *Influence of Nozzle Size*

Nozzle diameter determines extrusion width, layer contact area, and interlayer diffusion. At smaller diameters, narrow filaments cool rapidly, resulting in weak adhesion. Larger nozzles maintain heat longer at the interface, enhancing polymer chain entanglement, leading to stronger bonds. However, excess deposition reduces dimensional accuracy and causes surface waviness.[36, 37]

➢ *Trade-off Between Strength and Finish*

The experimental findings highlight a classic process trade-off: finer nozzles yield aesthetically pleasing prints but weaker structures, while coarse nozzles favor mechanical integrity at the cost of appearance. The 0.4 mm nozzle diameter offered the most balanced outcome, suitable for both functional and visual parts.

➢ *Microstructural Observation*

SEM images revealed distinct morphologies. The 0.2 mm samples displayed fine but loosely fused layers with micro-voids. The 0.4 mm samples exhibited strong fusion with limited porosity. The 0.6 mm specimens showed thicker layers and robust adhesion, though with some excess material accumulation at contours.

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VIII. OPTIMIZATION AND VALIDATION

Optimization through desirability function in RSM was used to simultaneously maximize tensile strength and minimize surface roughness.

➢ *The Desirability Value Peaked at 0.87 For:*

- Nozzle diameter: 0.4 mm
- Print speed: 50 mm/s
- Temperature: 200 °C

➢ *Validation Tests Under These Optimized Conditions Produced:*

- Tensile strength: 54.5 MPa
- Surface roughness: 6.7 µm

The small deviation (≤3%) from predicted values confirmed the model's reliability.

IX. COMPARATIVE PERFORMANCE

TABLE 2 Comparative Performance

Nozzle (mm)	Surface Roughness (µm)	Tensile Strength (MPa)	Dimensional Deviation (%)	Print Time (min)
0.2	4.3	48.5	0.32	150
0.4	6.8	54.1	0.51	120
0.6	11.2	57.3	0.89	95

This comparison illustrates the performance trade-off clearly. While the 0.6 mm nozzle saves 35% time, the 0.4 mm nozzle achieves the optimal compromise between performance and finish.

X. CONCLUSION

- Nozzle diameter significantly influences mechanical strength, surface quality, and dimensional accuracy in FDM printing.
- Smaller nozzles (0.2 mm) provide excellent surface finish but lower mechanical strength.
- Larger nozzles (0.6 mm) increase tensile strength due to better interlayer bonding but worsen print quality.
- The 0.4 mm nozzle yields an optimal balance of strength (≈54 MPa) and surface roughness (≈6.8 µm).
- Statistical analysis via RSM and ANOVA confirmed the dominant influence of nozzle diameter ($p < 0.001$).
- The developed regression model can guide parameter selection for applications demanding both aesthetics and mechanical reliability.

FUTURE ENHANCEMENTS

➢ *Future Investigations Should Explore:*

- The effect of layer orientation, infill pattern, and post-processing treatments on optimized nozzle performance.
- Multi-material printing and fiber-reinforced filaments to enhance strength further.
- Use of machine learning algorithms to predict print outcomes automatically for different nozzle configurations.
- Integration of in-situ monitoring (using sensors and cameras) to detect defects and adapt print parameters in real time.

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