Predictive modelling and analysis of roundness of cylindrical parts 3D printed with FDM technology

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ABSTRACT

KEYWORDS

3D Printing,
Roundness,
Fused Deposition,
Modelling,
Dimensional Accuracy,
Geometric Tolerance,
Additive Manufacturing,
Layer Thickness.

The most promising technology in the production environment today is additive manufacturing (AM). The term "3D printing" also applies to this technology. Layers of material are added to create components in additive manufacturing. With the development of technology, additive manufacturing is now used to create components out of metal, polymers, and composites in practically every industrial industry. It provides enormous design flexibility and produces intricate forms and components of sophisticated patterns. This article presents an approach to predict roundness and a dimension using regression Taguchi, Regression, Mean Effect Plots, and Surface Plots. It is observed during analysis that with a low p-value of 0.214, the ANOVA findings show that infill density, which is essential for obtaining the optimal print quality, has the greatest influence on the roundness of 3D-printed items. Although layer thickness does affect roundness, the effect is not as strong as it could be. Thinner layers, such as 0.14 mm, perform better than larger ones, increasing roundness by up to 8.41%. In contrast, printing speed has a minimal impact on roundness, as indicated by its p-value of 0.532. The contour plots advise aiming for an infill density between 74% and 80%, a layer thickness between 0.14 mm and 0.16 mm, and a printing speed between 90 mm/s and 100 mm/s to attain the best roundness.

1. Introduction

Rapid prototyping is a form of advanced manufacturing that uses a number of technologies and methodologies to create parts for a range of final applications. One of these cutting-edge manufacturing processes is additive manufacturing, which only consumes the material that is necessary and has the requisite dimensional accuracy (Patil et al., 2022). Rapid prototyping using Fused Deposition Modelling (FDM) is a technique for printing thermoplastics in three dimensions (Nagendra et al., 2021). The process steps for FDM are depicted in Fig. 1. The construction of the required object's CAD model is the first step in FDM. The STL file (with a.stl extension) is created from this CAD model in the following step. The STL file is then divided into a number of layers using the appropriate slicing software, and the object is created using a 3D printer. In the last step, fabricated parts are then undergo post-processing for cleaning and finishing based on their application (Deomore & Raykar, 2021; Patil et al., 2021; D'Addona et al. 2021; Raykar & D'Addona, 2020; Raykar et al. 2020).

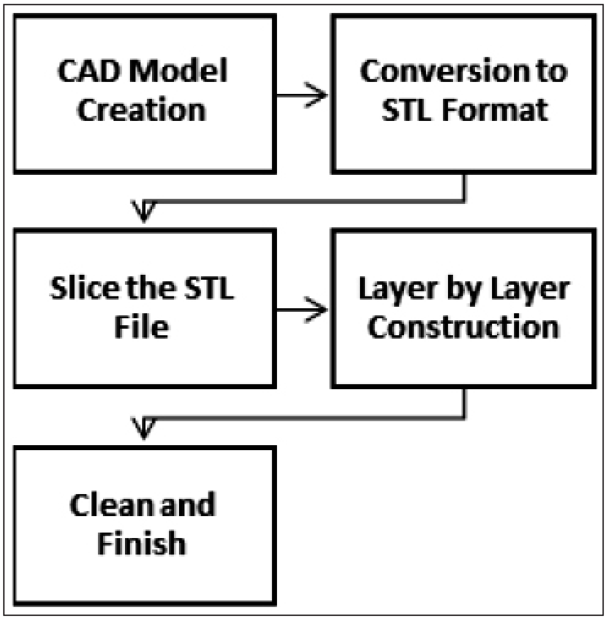

Fig. 1. Steps involved in FDM (Deomore & Raykar, 2020).

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The process parameters used have a substantially greater impact on the quality of the product produced using the Fused Deposition Modelling (FDM) approach (Nagendra & Ganesha Prasad, 2020). A key factor in establishing the functionality of goods made for industrial purposes, such as shafts, bearings, and pulleys, is geometric tolerance. For improved geometric qualities and application, it is crucial to choose a certain set of process parameters. Geometrical errors are significantly impacted by the orientation of the components, according to Boschetto and Bottini (2014, 2016). The results showed that vertical walls had the smallest variances. Increased deviations occur when the angle is less or more than 90 degrees.

Sood et al. (2011, 2009) evaluated the impact of numerous factors on geometrical accuracy using Design of Experiment (DoE) methodologies and found significant factors and efficient parameter configurations to lessen geometrical errors. Mahesh et al. (2004) introduced a geometry with flexible form surfaces that exhibit variations from nominal dimensions ranging from 5% to 15%. In one case, a form distortion caused a 2.5 mm divergence. Geometrical accuracy and process factors have not yet been properly investigated. Chinmay et al. (2022) analysis of variance (ANOVA), mean effect plots, and contour plots were used to examine the impact of a process parameter on the surface roughness of FDM parts. According to their research, construction orientation and layer thickness had the biggest effects on surface roughness. They came to the conclusion that the ideal working ranges for achieving surface roughness below 6 m were orientations 0 to 15 and 85 to 90, with layer thicknesses ranging from 0.12 to 0.16 mm and infill densities between 80% and 90%. 1.75 mm diameter filament and 0.4 mm nozzle diameter were employed. Both the methodical creation of dimensional tolerances for additive manufacturing processes and the optimisation of machine settings and manufacturing impacts to minimise dimensional deviations are goals of the study of dimensional tolerances (Lieneke et al., 2015). According to current dimensioning and tolerance standards (Ameta et al., 2015, Standard, 1984), a component part's size (size tolerance) and shape (geometric tolerance, encompassing form, orientation, and position) serve as indicators of how accurately its dimensions are. When fitting component components together, size variation is essential since size directly affects clearance conditions. Ollison and Berisso (2009) examined the relationship between construction direction, printhead life, and feature size in their investigation on cylindricity mistakes. They produced two components with diameters of 0.75 and 1 inches using three different orientation angles of 0, 45, and 90 degrees. After performing an ANOVA analysis on the components, it was shown that the cylindricity error was greatest at a build angle of 90 degrees and lowest at a build angle of 0 degrees.

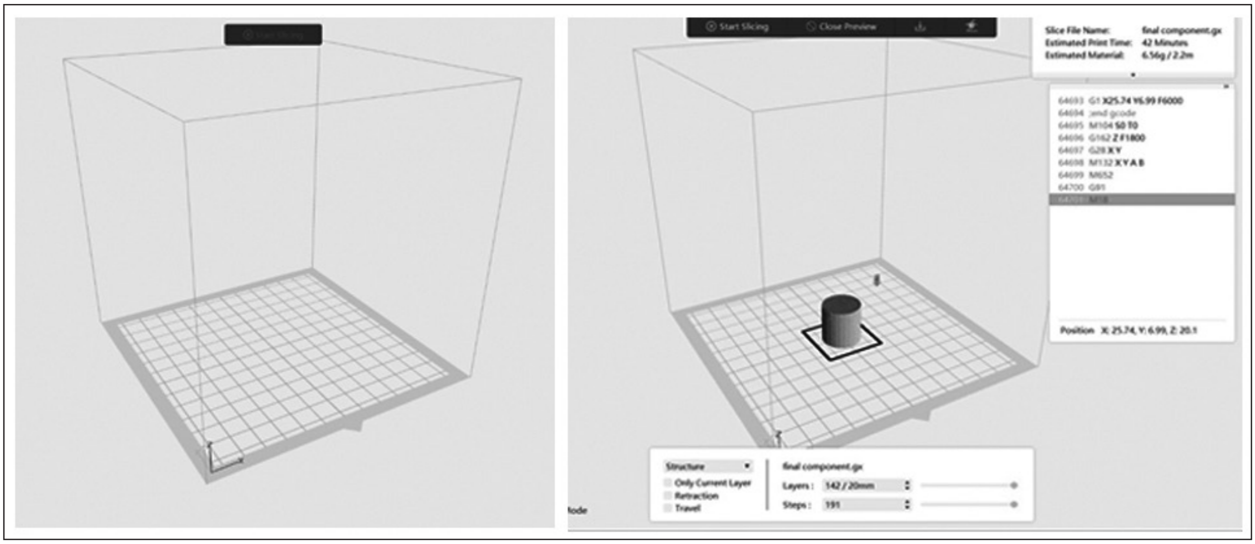
A survey of the literature reveals that little research has been done on the geometrical tolerances of cylindrical parts. The focus of the current research is on how different process variables affect geometrical tolerance, and dimension specifically how round and dimensionally correct a cylindrical PLA component is when produced using fused deposition modelling. Layer Thickness, Infill Percentage, and Print Speed are the three process parameters chosen for the current investigation based on prior research.

2. Experimental Setup

The details of experimental setup are given in Table 1 along with the specifications.

Table 1
Details of experimental work.

Item	Details
3D Printing technology	Fused Deposition Modelling
3D Printer	Flashforge Finder 3D printer (140 mm^3)
Filament Diameter	1.75 mm
Nozzle Diameter	0.4 mm
Slicing Software	Flashprint
File Type	STL
Nozzle Temperature	220^o C
Infill Pattern	Line
Shell Thickness	0.80 mm
Material	Polylactic Acid (PLA)
Specimen Specifications	Cylindrical Block (r= 10 mm, l=40 mm)
Roundness Measurement	Baker Type 302A dial gauge



Slice File Name: final component.gx
Estimated Print Time: 42 Minutes
Estimated Material: 6.56g / 2.2m

```
64693 G1 X25.74 Y6.99 F6000
64694 ;end gcode
64695 M104 S0 T0
64696 G162 Z F1800
64697 G28 X Y
64698 M132 X Y A B
64699 M652
64700 G91
```

Position X: 25.74, Y: 6.99, Z: 20.1

final component.gx
Layers : 142 / 20mm
Steps : 191

Fig. 2. Slicing view on flashprint slicer.

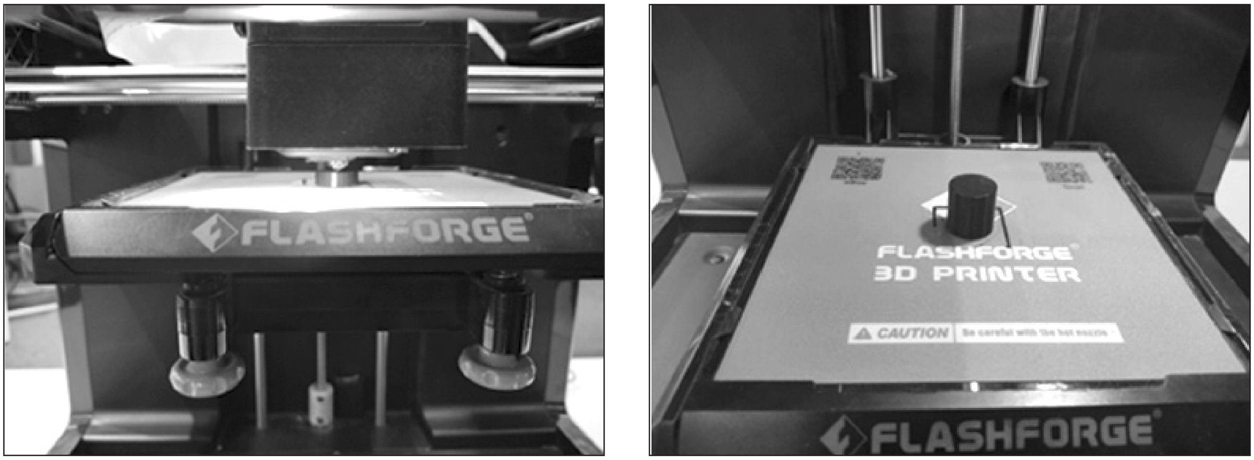


Fig. 3. View of actual printing on flashforge finder.

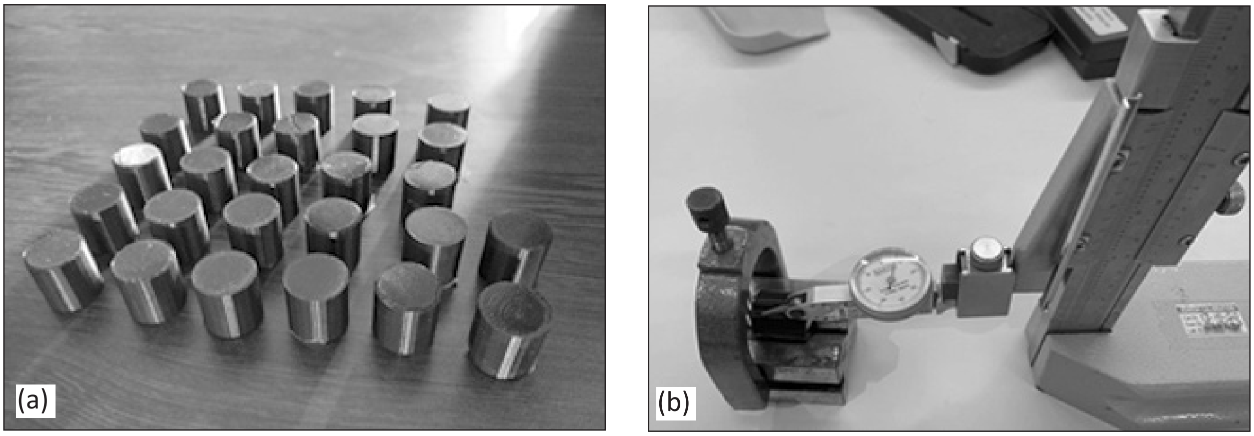


Fig. 4. (a). Printed components (b). Roundness inspection set up.

In Fig 2 - 4 shows slicinf details, view of printing and inspection set up respectively.

To assess effects of parameters on roundness of FDM printed parts three process parameters each of them having three levels are selected. These process parameters and their levels are given in Table 2. These parameters are selected on basis of trial experiments during which the gaps between the parameters are kept wide initially and then it is narrowed down and after that the final parameters which are selected for this investigation are shown in Table 2.

Taguchi L_{27} array is created using 3 factors at 3 levels for selected process parameters in free trial version of Minitab software. Table 3 shows the Taguchi L_{27} array.

The CAD based 3D model of cylindrical body of Length 40mm and Diameter 30mm of test specimen is sliced in Flashprint software using set of process parameters Layer Height, Infill Percentage and Printing Speed which is defined in Taguchi L27 array. Fig. 2 shows the slicing of cylindrical component in Flashprint version 5.

3. Results and Discussions

The ANOVA results shown in Table 4 indicates how different factors, like layer thickness, infill density, and printing speed, impact the roundness of the printed objects. In particular, the p-value for infill density is 0.214, which means it has the most significant effect on roundness among these factors. So, changes in infill density can noticeably affect the roundness of the prints. The p-value for layer thickness is 0.307, suggesting that it has a somewhat limited effect on roundness. While it does have an impact, it's not as influential as infill density. Lastly, the p-value for printing speed is 0.532, indicating that it has little effect on the roundness of the printed objects. In other words, adjusting the printing speed doesn't seem to make much of a difference in terms of roundness.

Table 2

Process parameters and their levels.

Process Parameters	**L1**	**L2**	**L3**
Layer height (mm)	0.14	0.16	0.18
Infill Density (%)	70	75	80
Print Speed (mm/sec)	90	95	100

Table 3

Taguchi L_9 array for selected parameters.

Layer Thickness (mm)	**Infill Density (%)**	**Printing Speed (mm/ sec.)**	**Roundness (mm)**
0.14	70	90	0.16
0.14	70	95	0.08
0.14	70	100	0.09
0.14	75	90	0.11
0.14	75	95	0.06
0.14	75	100	0.09
0.14	80	90	0.08
0.14	80	95	0.09
0.14	80	100	0.08
0.16	70	90	0.09
0.16	70	95	0.13
0.16	70	100	0.11
0.16	75	90	0.08
0.16	75	95	0.09
0.16	75	100	0.09
0.16	80	90	0.10
0.16	80	95	0.09
0.16	80	100	0.09
0.18	70	90	0.12
0.18	70	95	0.11
0.18	70	100	0.09
0.18	75	90	0.10
0.18	75	95	0.11
0.18	75	100	0.13
0.18	80	90	0.11
0.18	80	95	0.10
0.18	80	100	0.10

Table 4

ANOVA for roundness.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Layer Thickness (mm)	2	0.001008	0.000504	1.25	0.307
Infill Density (%)	2	0.001339	0.000670	1.67	0.214
Printing Speed (mm/sec.)	2	0.000524	0.000262	0.65	0.532
Error	20	0.008040	0.000402		
Total	26	0.010912			

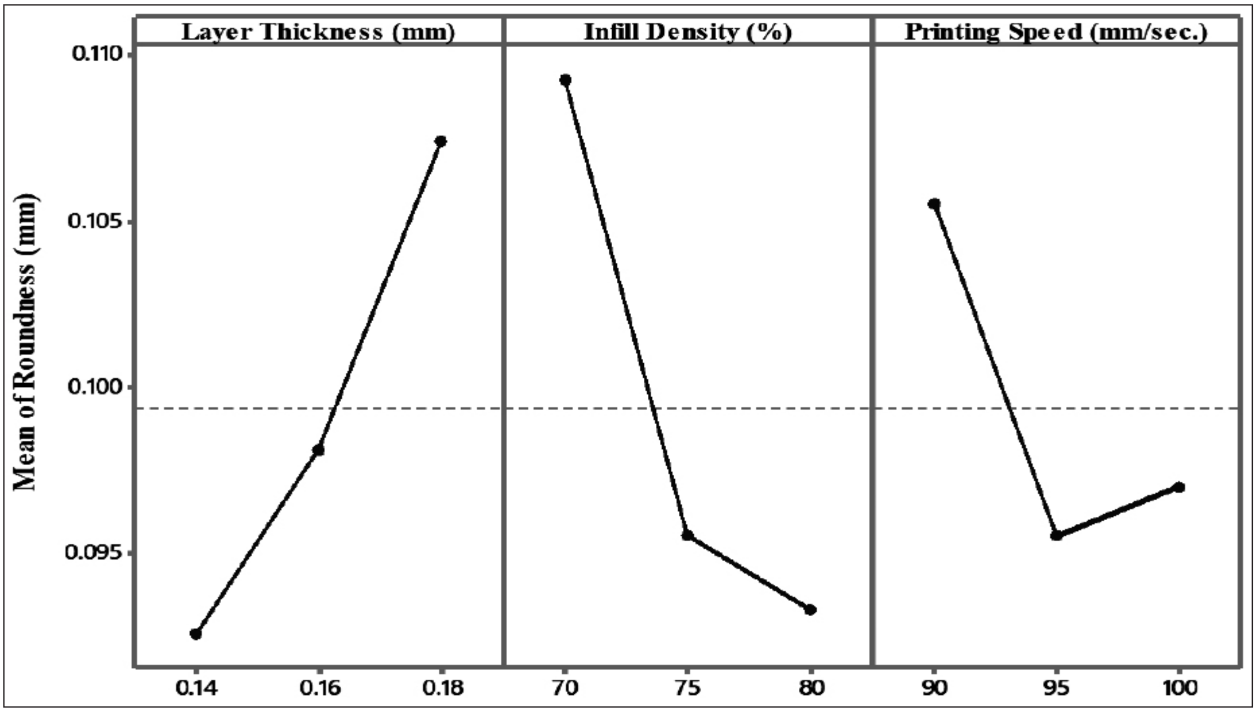


Fig. 5. Mean effect plot for roundness.

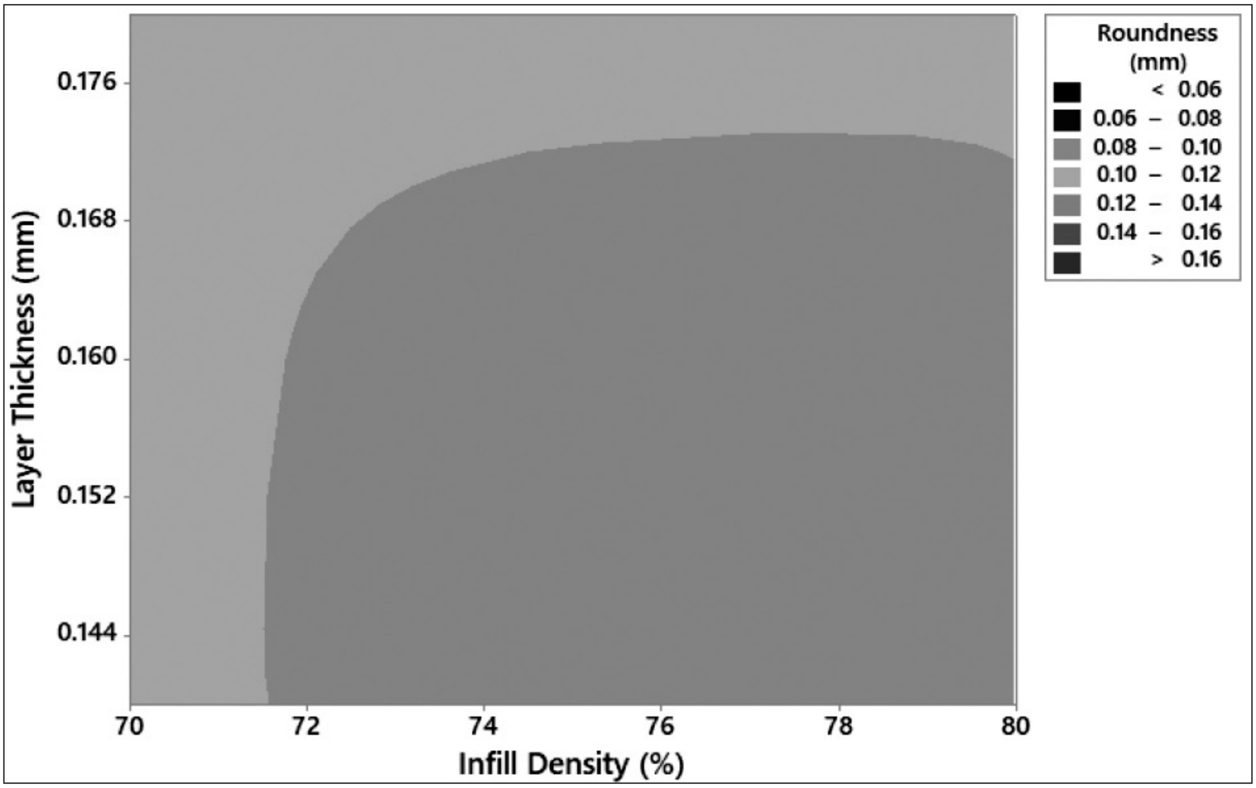


Fig. 6. Counter plot for roundness w.r.t layer thickness and infill density.

The mean of roundness is 0.092 mm at 0.14 mm layer thickness, 0.098 mm at 0.16 mm layer thickness, and 0.107 mm at 0.18 mm layer thickness, as illustrated in Fig. 4's Mean Effect Plot for Roundness values. Thus, at a layer thickness of 0.14 mm, the minimal mean roundness is revealed. In comparison to 0.14 mm layer thickness, there is a 6.12% increase in roundness at 0.16 mm layer thickness. Similar to the rise in roundness, the percentage increase at 0.18 mm layer thickness is 8.41 % higher than at 0.14 mm layer thickness. This suggests that thinner layers

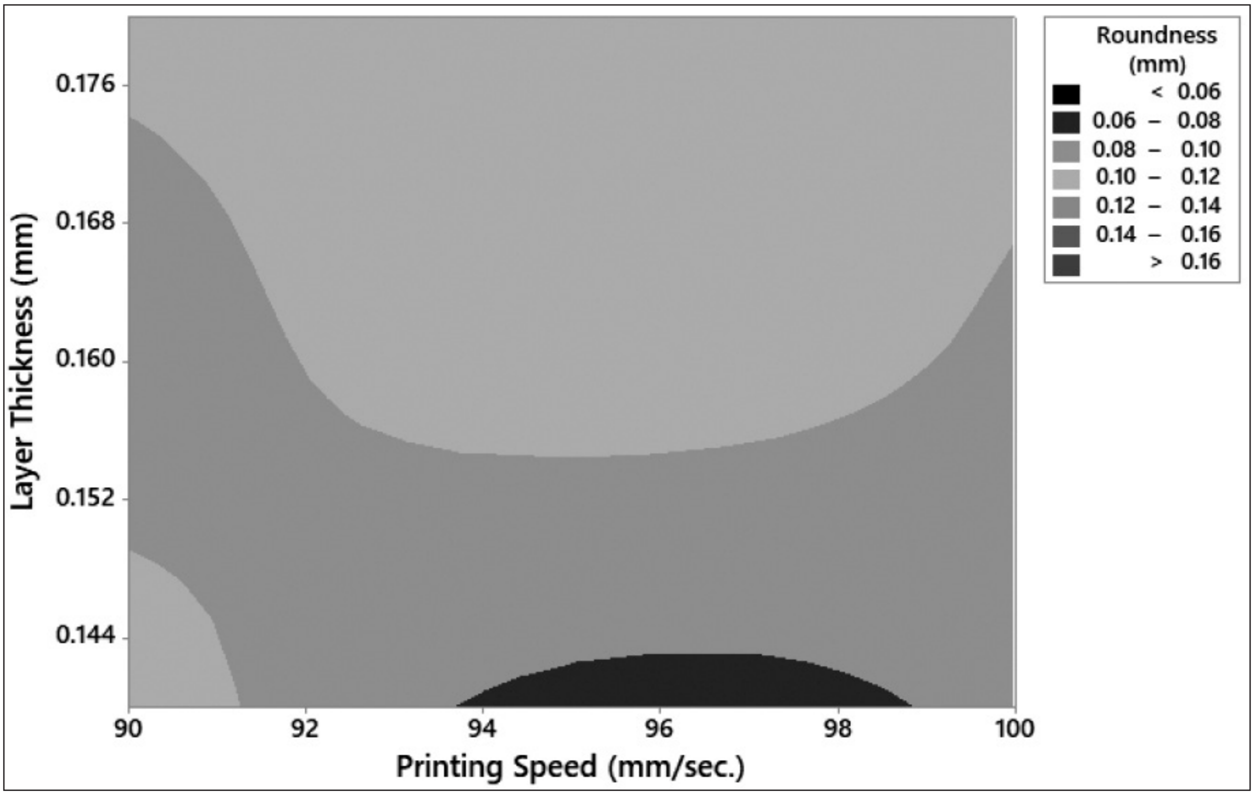


Fig. 7. Counter plot for roundness w.r.t layer thickness and printing speed.

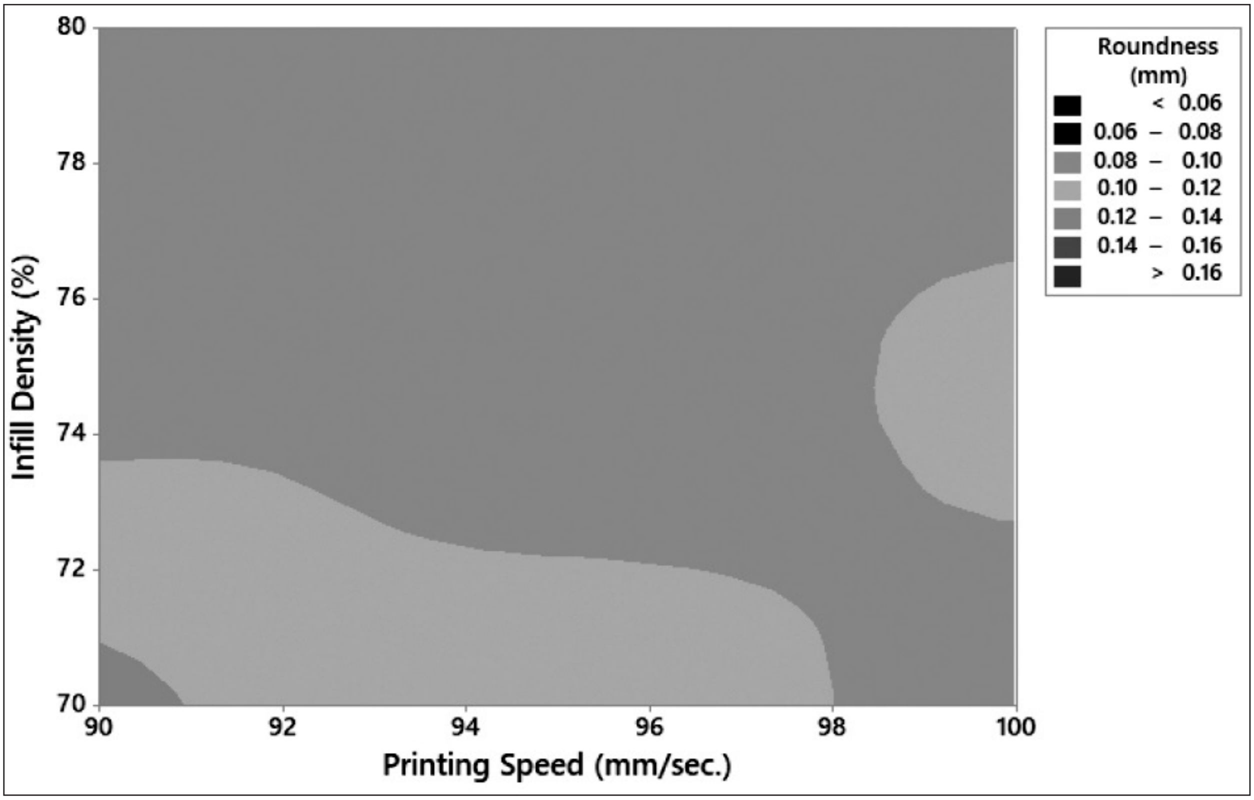


Fig. 8. Counter plot for roundness w.r.t infill density and printing speed.

produce better roundness. Therefore, a lower layer height creates a virtually round surface. The average roundness varies between 0.109 mm at an infill density of 70%, 0.095 mm at an infill density of 75%, and 0.093 mm at an infill density of 80%. As a result, 80% infill density is where the least mean roundness is discovered. Therefore as compared 70 % infill density the roundness it is reduced by 12.84% at 75 %; and at 80% infill density, it is reduced by 2.10%. Therefore higher Infill % gives better results for roundness. Highest roundness with respect to printing speed is at 90mm/sec i.e., 0.105mm and lowest roundness is seen at 95mm/sec i.e. 0.095mm.

To find out workable range for roundness for continuous variables in this investigation which are printing speed, infill % and layer thickness contour plots are drawn for roundness based on these variables. These plots are shown in Figure 6 to 8. From contour plots workable range of process parameters for better results of roundness can be identified. From the roundness values measure after printing that are shown in Table 2, the smaller values for roundness are less than 0.10 mm, and the range for contour plot for roundness is fixed as less than 0.06 mm, 0.06 mm to 0.08 mm, 0.08 mm to 0.10 mm, and larger values above 0.10 mm. So the working range of roundness for parameter under investigation can be identified is less than 0.06 mm and between 0.06 to 0.10 µm which are in faint and dark blue colour, from faint green to dark colour the surface roughness range is more than 0.10 µm. With this the workable ranges of process parameters identified from contour plots are infill % of 74 % to 80 %, layer thickness of 0.14 mm to 0.16 mm and printing speed of 90 mm/s to 100 mm/s.

The regression equation shown below gives the idea about influencing parameters on roundness

Roundness (mm) = 0.240 + 0.370 Layer Thickness (mm) - 0.001593 Infill Density (%) - 0.000852 Printing Speed (mm/sec.)

The presented regression equation links various important printing factors to the “Roundness” of a 3D-printed item, measured in millimetres (mm). With a positive coefficient of 0.370, the equation shows that Roundness is influenced by “Layer Thickness” in millimetres, indicating that as layer thickness rises, so does Roundness. In contrast, “Infill Density” in percent, with a coefficient of -0.001593, and “Printing Speed” in millimetres per second, with a coefficient of -0.000852, are inversely correlated with “Roundness,” indicating that higher infill density and faster printing are linked to lower Roundness.

4. Conclusions

Following conclusions are drawn from the investigation.

1. As evidenced by the relatively low p-value of 0.214 in the ANOVA results, infill density appears to be the factor that most significantly affects the roundness of 3D-printed items. The roundness can be significantly affected by modifying infill density, making it a key factor to take into account for obtaining the required print quality.
2. Although layer thickness has only a sporadic effects on roundness, it is still an important component. With an increase in roundness of up to 8.41% at the thickest layer setting, thinner layers, such as 0.14 mm, produce better roundness than larger layers, like 0.16 mm and 0.18 mm.
3. Limited Effect of Printing Speed: According to the statistics, with a p-value of 0.532, printing speed had the least impact on roundness. The roundness of the printed items is not greatly affected by changing the printing speed, indicating that this may be a less important parameter to adjust for better roundness.
4. Contour plots show the practical ranges of process parameters for roundness. Optimal Parameter Ranges. Infill density should be between 74% and 80%, layer thickness should be between 0.14 mm and 0.16 mm, and printing speed should be between 90 mm/s and 100 mm/s for the best results. These ranges can aid in giving 3D-printed things the desired roundness.

References

Ameta, G., Lipman, R., Moylan, S., & Witherell, P. (2015). Investigating the role of geometric dimensioning and tolerancing in additive manufacturing. *Journal of Mechanical Design*, *137*(11), 111401.

Boschetto, A., & Bottini, L. (2014). Accuracy prediction in fused deposition modeling. *The International Journal of Advanced Manufacturing Technology*, *73*, 913-928.

Boschetto, A., & Bottini, L. (2016). Design for manufacturing of surfaces to improve accuracy in fused deposition modeling. *Robotics and Computer-Integrated Manufacturing*, *37*, 103-114.

D'Addona, D. M., Raykar, S. J., Singh, D., & Kramar, D. (2021). Multi objective optimization of fused deposition modeling process parameters with desirability function. *Procedia CIRP*, *99*, 707-710.

Deomore, S. A., & Raykar, S. J. (2021). Multi-criteria decision making paradigm for selection of best printing parameters of fused deposition modeling. *Materials Today: Proceedings*, *44*, 2562-2565.

Lieneke, T., Adam, G. A. O., Leuders, S., Knoop, F., Josupeit, S., Delfs, P., ... & Zimmer, D. (2015). Systematical determination of tolerances for additive manufacturing by measuring linear dimensions. In *2015 International Solid Freeform Fabrication Symposium*. University of Texas at Austin.

Mahesh, M., Wong, Y. S., Fuh, J. Y. H., & Loh, H. T. (2004). Benchmarking for comparative evaluation of RP systems and processes. *Rapid Prototyping Journal*, *10*(2), 123-135.

Nagendra, J., & Prasad, M. G. (2020). FDM process parameter optimization by Taguchi technique for augmenting the mechanical properties of nylon–aramid composite used as filament material. *Journal of the Institution of Engineers (India): Series C*, *101*, 313-322.

Nagendra, J., Srinath, M. K., Sujeeth, S., Naresh, K. S., & Prasad, M. G. (2021). Optimization of process parameters and evaluation of surface roughness for 3D printed nylon-aramid composite. *Materials Today: Proceedings*, *44*, 674-682.

Ollison, T., & Berisso, K. (2009). Three-dimensional printing build variables that impact cylindricity. *Journal of Industrial Technology*, *26*(1).

Patil, P., Raykar, S. J., Bhamu, J., & Singh, D. (2022). Modeling and analysis of surface roughness in fused deposition modeling based on infill patterns.

Patil, P., Singh, D., Raykar, S. J., & Bhamu, J. (2021). Multi-objective optimization of process parameters of fused deposition modeling (FDM) for printing polylactic acid (PLA) polymer components. *Materials Today: Proceedings*, *45*, 4880-4885.

Raykar, S. J., & D'Addona, D. M. (2020). Selection of best printing parameters of fused deposition modeling using VIKOR. *Materials Today: Proceedings*, *27*, 344-347.

Raykar, S. J., Narke, M. M., Desai, S. B., & Warke, S. S. (2020). Manufacturing of 3D printed sports helmet. In *Techno-Societal 2018: Proceedings of the 2nd International Conference on Advanced Technologies for Societal Applications-Volume 2* (pp. 771-778). Springer International Publishing.

Sood, A. K. (2011). *Study on parametric optimization of fused deposition modelling (FDM) process* (Doctoral dissertation).

Sood, A. K., Ohdar, R. K., & Mahapatra, S. S. (2009). Improving dimensional accuracy of fused deposition modelling processed part using grey Taguchi method. *Materials & design*, *30*(10), 4243-4252.

Standard, A. (1984). AS1100, Technical drawing, part 201-1984, mechanical drawing. *The Standards Association of Australia, Sydney*.

Sutar, C. V., Mandavkar, A. A., Patil, S. B., Mohite, T. U., Patole, T. A., & Raykar, S. (2022). Analysis and prediction of working range of process parameters for surface roughness of 3D printed parts with fused deposition modelling. *Journal of Manufacturing Engineering*, *17*(2), 044-050.

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