Optimization of FDM Parameters for Enhancing Dimensional Accuracy of Spur Gears Using the Taguchi Method

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Abstract. 3D Printing Technology, particularly Fused Deposition Modeling (FDM), has experienced rapid development. However, the layer-by-layer stacking process often hinders the dimensional accuracy of the produced objects. This research aims to improve the dimensional accuracy of Spur Gears (ISO - Spur gear 1.75M 40T 20PA 8FW) by optimizing FDM parameters. The Taguchi design of the experiment's method was used to identify the optimal combination of layer thickness, infill density, and wall thickness parameters. Experiments were conducted using a Creality CR-10S Pro V2 3D printer with PLA+ filament. Dimensional accuracy was evaluated using a basic tangent system with a micrometer measuring instrument. Data analysis was performed using JMP 18.0.1 software with the "smaller is better" criterion to minimize dimensional errors. The results showed that layer thickness has the most significant impact on the dimensional accuracy of the spur gears. The optimal parameter combination obtained was a layer thickness of 0.2 mm, an infill density of 60%, and a wall thickness of 0.4 mm.

Keywords: 3D Printing, Dimensional Accuracy, Spur Gears, Taguchi.

1 Introduction

3D printing technology, particularly Fused Deposition Modelling (FDM), has developed rapidly in recent years. Fused Deposition Modelling (FDM) has a working principle of extruding thermoplastic through a hot nozzle at melting temperature, and then the product is made layer by layer [1].

Although this technology offers flexibility and efficiency in prototyping and final product manufacturing, the 3DP FDM machine type has a disadvantage because this technology uses a building process per layer so that the resulting surface looks to have lines that show the boundaries between layers so that the resulting product is less aesthetic in the 3D printing process with FDM [2]. These layer boundaries result from layer-by-layer printing. On the downside, these layer boundaries affect aesthetic quality and mechanical performance [3]. This condition can negatively impact performance, especially in applications that require high precision.

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Spur gears are mechanical components used to transfer rotational motion between two shafts [4]. Dimensional accuracy on spur gears is critical to ensure optimal performance and avoid premature wear or damage [5]. Dimensional deviations can cause imbalances in power transmission and potentially reduce the efficiency of mechanical systems.

This research aims to improve the dimensional accuracy of 3D-printed spur gears using FDM technology. The optimization of printing parameters is expected to reduce dimensional errors and ensure better quality in the resulting parts. The Taguchi design of the experiment's method is used to identify the optimal combination of parameters that can improve the dimensional accuracy of spur gears. The parameters varied in this study and included layer thickness, infill density, and wall thickness. Experiments were conducted using a Creality CR-10S Pro V2 3D printer with PLA+ filament.

2 Material and Methods

The researcher carried out the research work at the Halpoint Workshop in Yogyakarta. The methods used in this research include literature, design, and experimentation on Spur Gears specimens made using an FDM 3D printer. Systematically, this can be shown in the research flow chart shown in Fig. 1.

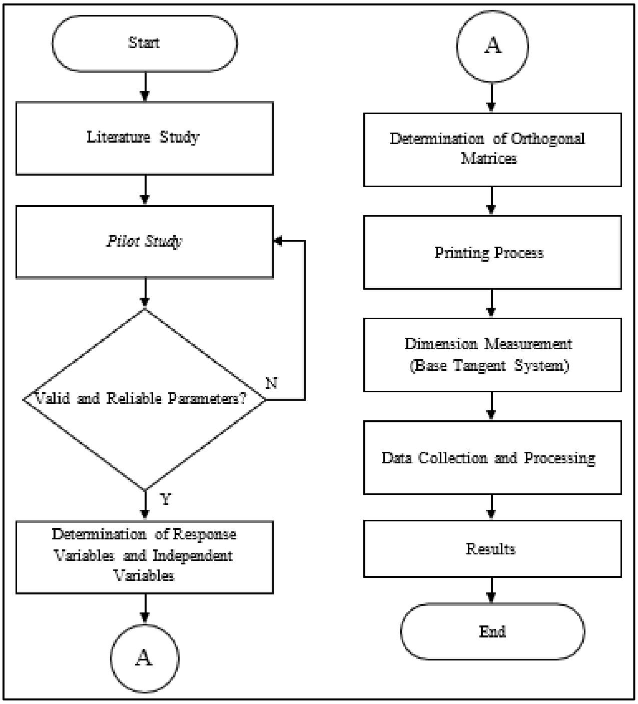

Fig. 1. Research Flowchart

2.1 Test Specimen Measurement

This research uses a 3D printer with FDM (Fused Deposition Modeling) technology Creality CR-10S Pro V2, as shown in Fig. 2. Then, the object produced comes from PLA + filament type e-sun brand.

Fig. 2. 3DP Machine FDM Creality CR-10S Pro V2

Spur Gears (ISO - Spur gear 1.75M 40T 20PA 8FW) is a reference in making test specimens in this study, as shown in Fig. 3. This measurement aims to determine the dimensional deviations in the test specimens from 3D printers and the main factors that affect dimensional deviations measured utilizing a base tangent system with a measuring instrument as a micrometer. The measurement process can be seen in Fig. 4.

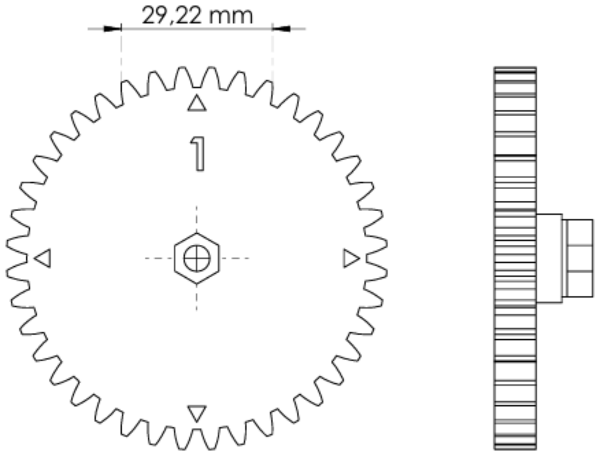

Fig. 3. Specimen ISO - Spur gear 1.75M 40T 20PA 8FW

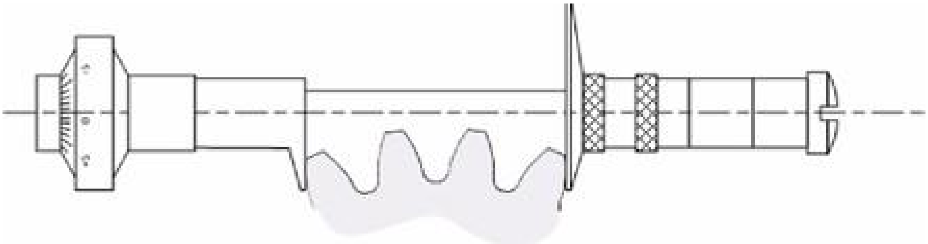

Fig. 4. Base Tangent System Measurement [6]

The process of making specimens using a 3D printer through 3 stages, namely:

- 3D design of test specimen with Solidworks 2022 software.
- Slicing of 3D test specimens with Cura Ultimaker V.5.0.4 software
- Printing process of test specimen using FDM 3D printer.

The orthogonal array is a matrix of numbers that has a special meaning. In determining the orthogonal array matrix, paying attention to the number of factors and levels used in conducting research is necessary—the general form of the orthogonal array matrix model in Equation 1.

$$La\ (b^c) \tag{1}$$

Where:

L = Latin symbol of the matrix = number of trials
B = number of levels
C = number of factors

In determining the orthogonal array used in this study, four factors and 3 levels in each 3DP type were used, thus using an orthogonal array. L9 (3^4). After that, each factor is input into the general matrix of the orthogonal array L9, as shown in Table 1.

Table 1. Optimized Independent Variables

Factor	**Level**		
	Level 1	**Level 2**	**Level 3**
Layer Thickness (mm)	0.16	0.2	0.28
Infill Density (%)	20	40	60
Wall Thickness (mm)	0.2	0.3	0.4

While the fixed variables in the formation of test specimens are as follows:
Printing Speed = 60 mm/s
Nozzle Temperature = 200^0 C
Bed Temperature = 50^0 C

2.2 Tools and Materials

Tools and Materials (mm/s) support used in this study are:

- 3D Printing FDM Creality CR-10S Pro V2

- Outside Micrometer 25-50 mm
- Software Solidworks Student Version 2022.
- Software JMP Student version 18 Trial Version
- Software Cura Ultimaker V 5.0.4
- Filament PLA+ e-SUN.

Table 2. Receiver Circuit Path

LoRa RFM95W PIN	NodeMCU ESP8266 PINS
VCC	3.3V
GND	GND
SCK	D5
MISO	D6
MOTION	D7
NSS	D8
RST	D4
DIO0	D3

3 Results

After taking measurements with the base tangent system on the gear specimens for four replications, the deviation between the actual and design dimensions showing variations in each replication can be seen in Table 3. Product specimens were then measured in length using a micrometer with a precision of 0.01 mm.

Table 3. Measurement Data per Replication

Sample	Layer Thickness (mm)	Infill Density (%)	Wall Thickness (mm)	Run 1	Run 2	Run 3	Run 4
1	0.16	20	0.2	0.0009	0.0004	0.0016	0.0004
2	0.16	40	0.3	0.0009	0.0009	0.0004	0.0000
3	0.16	60	0.4	0.0100	0.0121	0.0049	0.0110
4	0.2	20	0.3	0.0064	0.0036	0.0064	0.0064
5	0.2	40	0.4	0.0081	0.0144	0.0090	0.0049
6	0.2	60	0.2	0.0420	0.0324	0.0484	0.0196
7	0.28	20	0.4	0.0064	0.0049	0.0042	0.0049
8	0.28	40	0.2	0.0004	0.0016	0.0025	0.0004
9	0.28	60	0.3	0.0036	0.0009	0.0064	0.0004

3.1 Calculation of Mean and SN/ Ratio

Table 4 presents the results of the analyses, including the mean values and signal-to-noise ratio (SNR) calculated using JMP V.18 software. This study analyzed three factors, Layer Thickness, Filler Density, and Wall Thickness, to assess their influence on the dimensional accuracy of spur gears. Based on the ANOVA results, the mean value indicates the average dimensional accuracy for each factor level, while the SNR value indicates the robustness of dimensional accuracy under various conditions.

Table 4. Mean and S/N Ratio.

Sample	Layer Thickness (mm)	Infill Density (%)	Wall Thickness (mm)	Pattern	Run 1	Run 2	Run 3	Run 4	Mean	SN Ratio
1	0.16	20	0.2	−−−	0.0009	0.0004	0.0016	0.0004	0.0008	60.3503
2	0.16	40	0.3	−00	0.0009	0.0009	0.0004	0.0000	0.0006	63.5149
3	0.16	60	0.4	−++	0.0100	0.0121	0.0049	0.0110	0.0095	40.0881
4	0.2	20	0.3	0−0	0.0064	0.0036	0.0064	0.0064	0.0057	44.6903
5	0.2	40	0.4	00+	0.0081	0.0144	0.0090	0.0049	0.0091	40.2407
6	0.2	60	0.2	0+−	0.0420	0.0324	0.0484	0.0196	0.0356	28.5835
7	0.28	20	0.4	+−+	0.0064	0.0049	0.0042	0.0049	0.0051	45.7336
8	0.28	40	0.2	+0−	0.0004	0.0016	0.0025	0.0004	0.0012	56.4159
9	0.28	60	0.3	0	0.0036	0.0009	0.0064	0.0004	0.0028	48.6257

3.2 SNR Normality Test

Based on the results in Fig. 5. shows the relationship between actual and predicted signal-to-noise (SN) ratio values, with key metrics such as an RMSE of 3.377, R^2 of 0.98, and a P-value of 0.0683. The red regression line illustrates a strong linear relationship between the data, supported by the high R^2 value, indicating that the predictions closely match the actual values. The distribution of data points around the regression line and the red-shaded confidence intervals suggests minimal variation. The P-value, greater than 0.05, indicates no significant evidence to reject the hypothesis of residual normality, implying that the residuals likely follow a normal distribution.

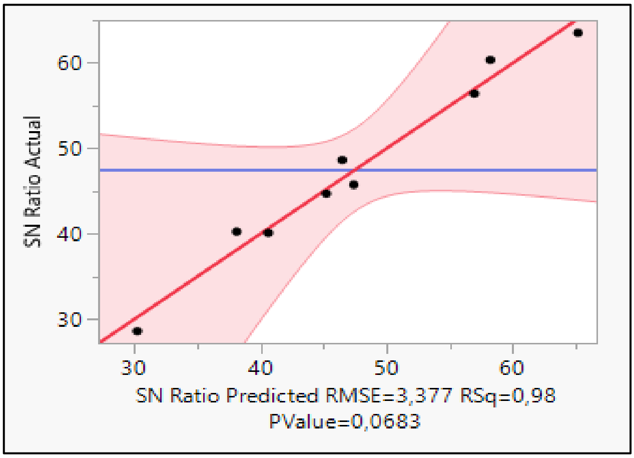

Fig. 5. Normality Test

3.3 ANOVA Test

A hypothesis test will be carried out to interpret the results of the ANOVA calculation. The following hypothesis test is used in making decisions in this study.

1. Layer Thickness (X1)
   H0: There is no average difference between layer thickness and the dimensional accuracy of spurs gear.
   H1: There is an average difference between layer thickness and the dimensional accuracy of spurs gear.
2. Infill Density (X2)
   H0: There is no average difference between infill density and the dimensional accuracy of spur gear.
   H1: There is an average difference between infill density and the dimensional accuracy of the spurs gear.
3. Wall Thickness (X3)
   H0: There is no average difference between wall thickness and the dimensional accuracy of the spur gear.
   H1: There is an average difference between wall thickness and the dimensional accuracy of the spur gear.

Table 5. Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Layer Thickness	2	2	456.23163	20.0026	0.0476*
Infill Density	2	2	338.58088	14.8445	0.0631
Wall Thickness	2	2	161.16793	7.0661	0.1240

Based on the results of the ANOVA table, we can analyze the effects of each factor (Layer Thickness, Infill Density, and Wall Thickness) on the dimensional accuracy of spur gears. For Layer Thickness (X1), the F-ratio is 20.0026 with a p-value of 0.0476, below the significance level of 0.05. This result suggests that we reject the null hypothesis (H0) and accept the alternative hypothesis (H1), indicating a significant average difference between layer thickness and the dimensional accuracy of the spur gears. For Infill Density (X2), the F-ratio is 14.8445 with a p-value of 0.0631 above 0.05. We fail to reject the null hypothesis, indicating no significant average difference between infill density and dimensional accuracy. Finally, for wall thickness (X3), the F-ratio is 7.0661 with a p-value of 0.1240 and above 0.05. We fail to reject the null hypothesis, indicating no significant average difference between wall thickness and dimensional accuracy. Thus, layer thickness has a substantial effect on dimensional accuracy.

The next step is to analyze the S/N ratio response with the characteristics of the more minor, the better the quality, and to determine the optimal control factor for dimensional accuracy of the mold using JMP software. Fig. 6 shows the results of the data analysis. The optimal parameter combinations obtained were 0.2 mm layer thickness, 60% infill density, and 0.4 mm wall thickness.

4 Discussion

The SNR values at both levels (High or low) of each factor were compared to decide which factor setting or level to maximize the output response. According to the main effect plot for mean and SNR, as shown in Fig. 6, the optimum conditions for the controllable factors based on the maximum desirability results of JMP software, layer thickness (X1), should be placed at a low level. In contrast, infill density (X2) and wall thickness (C) should be placed at the Middle level. This result means maximum accuracy will be achieved when factors X1 = 0.2, X2 = 60 and X3 = 0.4.

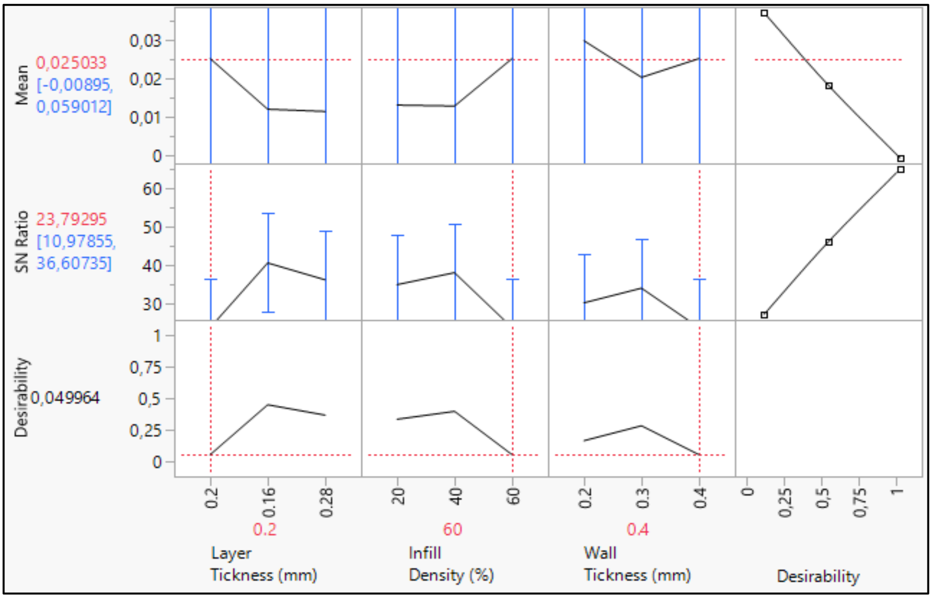

Fig. 6. S/N Ratio for Dimensional Accuracy

5 Conclusions

Based on the ANOVA analysis, it can be concluded that Layer Thickness (X1) significantly affects the dimensional accuracy of spur gears, as indicated by a p-value of 0.0476 below the 0.05 threshold. This result confirms that variations in layer thickness led to meaningful differences in gear accuracy. However, Infill Density (X2) and Wall Thickness (X3) do not show statistically significant effects, with p-values of 0.0631 and 0.1240, respectively, meaning their influence on dimensional accuracy is negligible under the tested conditions. The optimal parameter combination to achieve the best dimensional accuracy is a 0. 2 mm layer thickness, 60% infill density, and 0.4 mm wall thickness. This result suggests that among the factors studied, focusing on layer thickness adjustments is crucial for improving dimensional accuracy in 3D-printed spur gears, while infill density and wall thickness play a less critical role

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

References

1. Pristiansyah, P., Hasdiansah, H., Sugiyarto, S.: Optimasi Parameter Proses 3D Printing FDM Terhadap Akurasi Dimensi Menggunakan Filament Eflex. Manutech J. Teknol. Manufaktur **11**, 33–40 (2019).
2. Hasdiansah, H. & Sugiyarto, S.: Pengaruh Setting Parameter pada Slicing Software terhadap Surface Roughness Objek 3D Printing Menggunakan Metode Taguchi. J. Rekayasa Mesin **16**, 319–328 (2021).
3. Nasser, M., Rezg, M. Ben, Fellah, M. & Montagne, A.: Impact of infill strategy and process parameters on selectivity and performance of PLA structures obtained by 3D printing. Int. J. Adv. Manuf. Technol. **135**, 5499–5514 (2024).
4. Aero Engineering: Spur Gear. Indonesia (2022).
5. Rodrigues, G. W. P. *et al.* Analysis of the influence of mechanical element discontinuities on unbalancing. J. Eng. Exact Sci. **10**, 18309 (2024).
6. Junaidi, J.: Metrologi dan Pengukuran. Universitas Harapan Medan Press, Medan (2018).