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Optimization of 3D Printing Parameters for PLA Spur Gears using the Taguchi Method and Response Surface Methodology

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ABSTRACT

The dimensional accuracy of 3D-printed components is a significant challenge in precision engineering, particularly for functional parts such as spur gears. Variations in printing parameters often result in dimensional deviations, which can compromise the performance and reliability of the final product. This research investigates the influence of key 3D printing parameters—layer thickness, infill density, and printing speed—on the dimensional accuracy of polylactic acid (PLA) spur gears. The study employed the Taguchi Method, using an L9 orthogonal array, to identify critical factors and their interactions. At the same time, Response Surface Methodology (RSM) was utilized to develop a detailed response model for optimization. Findings revealed that printing speed significantly impacted dimensional accuracy, layer thickness, and infill density. By optimizing these parameters, substantial improvements in dimensional precision were achieved, reducing deviations and enhancing overall quality. The optimized settings demonstrate the potential for refining 3D printing processes to produce precise and reliable components. This study underscores the importance of statistical approaches in additive manufacturing and offers valuable insights for industries seeking to produce high-quality functional parts.

1. Introduction

Polymer gears have become increasingly prominent in various industrial applications due to their inherent advantages, such as reduced noise and vibration, self-lubrication, low weight, and cost-effective manufacturing. These features make them ideal for use in automotive components, office equipment, household appliances, and even advanced technologies such as industrial robots and medical devices [1-3]. Among the various polymer materials, polylactic acid (PLA) has gained considerable attention due to its biodegradability, mechanical reliability, and suitability for additive manufacturing processes.

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With the advent of 3D printing technologies, particularly Fused Filament Fabrication (FFF), the production of customized polymer gears has become more accessible, enabling greater design flexibility and rapid prototyping. However, despite these technological advancements, the manufacturing of polymer gears through 3D printing still faces critical challenges—chief among them is achieving high dimensional accuracy, which is essential for the functional performance and longevity of gear systems. Inaccuracies can lead to misalignment, uneven load distribution, increased wear, and ultimately, failure in precision-critical applications.

A significant limitation in current practice lies in the continued reliance on design standards originally developed for metal gears, which do not fully account for the distinct thermal and mechanical behaviors of polymer materials like PLA [2]. In addition, process parameters in 3D printing—such as layer thickness, infill density, and printing speed—play a crucial role in determining the final dimensional quality of printed parts. While some previous studies have examined the impact of individual parameters on general print quality, few have comprehensively analyzed their combined effects on the dimensional accuracy of PLA spur gears, a critical aspect for functional mechanical components.

More importantly, there remains a lack of studies employing robust statistical optimization techniques to systematically explore the parameter space and model the relationships between process inputs and dimensional accuracy outcomes. The use of integrated statistical tools such as the Taguchi Method and Response Surface Methodology (RSM) is notably limited in the context of PLA gear optimization, despite their proven utility in other areas of additive manufacturing. This research gap highlights the need for a focused study that not only quantifies the influence of key parameters but also provides an optimized framework for improving the dimensional precision of PLA gears.

The main objective of this study is to optimize the dimensional accuracy of PLA spur gears produced through FFF 3D printing. Specifically, this research aims to evaluate the effects of key printing parameters—layer thickness, infill density, and printing speed—on the dimensional accuracy of PLA spur gears. It also seeks to identify the most influential parameter affecting dimensional accuracy using the Taguchi Method. In addition, the study intends to develop a predictive optimization model using Response Surface Methodology (RSM) and to determine the optimal combination of printing parameters that minimizes dimensional deviations. Finally, the study aims to provide practical recommendations for improving the quality of 3D-printed PLA gears for use in precision applications.

This study contributes to the field of additive manufacturing by addressing the need for dimensional precision in 3D-printed functional components. By focusing on PLA spur gears, the research not only enhances the applicability of biodegradable materials in precision engineering but also provides a statistically validated framework for process optimization. The findings are expected to benefit industries involved in rapid prototyping, sustainable product development, and the production of lightweight, customized mechanical components.

2. Literature Review

2.1 Polymer Gears in Industrial Applications

Polymer gears, particularly those made from materials like ABS, PLA, and nylon, have gained traction due to their advantages over metal gears. For instance, they are lightweight, have low inertia, and offer greater operational efficiency. Gears made of polymers are increasingly preferred in automotive parts, paper mills, and domestic appliances, where noise reduction and lubrication-free operation are paramount [1]. The ability to absorb shocks and vibrations also contributes to their adoption in high-stress environments like robotics and diagnostic equipment [3]. PLA, in particular, has emerged as a favorable material for gear production because of its ease of fabrication, biodegradability, and excellent mechanical properties [4]. However, challenges remain in enhancing its wear resistance, which is crucial for improving the long-term performance of PLA-based gears. This highlights the need to optimize material properties and manufacturing processes to achieve gears that perform reliably in demanding environments. Polymer gears can be an alternative to steel gears in a wide range of devices and equipment requiring low loads. Therefore, the failures that polymer gears exhibit are different from those of steel gears. The types of failures can be detected by monitoring corrosion, weight loss, microstructure, and temperature detection [5].

Polymer gears are effective components in industrial machines for power transmission and are considered successful alternatives to metal gears. Three different polymer materials replace metallic gears in the drive mechanism for better performance in geared lathe machines, such as Nylatron, Nylon 66, and Polytetrafluoroethylene [6]. Recently, polymer gears have been widely used in medium- or heavy-duty applications due to weight reduction in transmission systems due to lower cost and noise than metal gears. In the current industry, proposing a cost-effective approach to manufacturing polymer gears is an important research issue [7].

Much of modern technology relies on more traditional equipment to get the job done, given the proliferation of electronics. For example, gears still play a significant role in many essential machines, from wind farms to heat pumps. Many gears are made of plastic to save cost and weight. Different materials can be used to manufacture polymer spur gears using the FDM process. The most important of these materials are ABS (Acrylonitrile butadiene styrene), PLA (Polylactic acid), and NYLON [2]. Producing sufficient precision and durability gears to serve in contemporary mechatronic applications in automotive, medical equipment, and many other industries is a significant challenge. These materials are POM, PA6, PA66, PEEK, reinforced plastics, etc., and steel [8]. The use of polymer gears in current vehicle systems is almost exclusively limited to applications with limited power transmission, such as engines. The scope of application is expanding to include the development of a transmission for use in a small electric vehicle of the 7Le energy class with the application of polymer gears in mind.

2.2 3D Printing Technology in Gear Manufacturing

The integration of 3D printing technology, specifically FFF, has significantly impacted the manufacturing of polymer gears, offering advantages in cost-effectiveness and design flexibility. A key study by Hanon *et al.,* [9] demonstrated that FDM-based 3D printers could produce components with high dimensional accuracy, making them a viable option for manufacturing functional parts like gears. The study emphasized the potential of commercial FDM printers, mainly when precise printing parameters are used. This potential is further explored by Muminović *et al.,* [10], who identified the critical role of 3D printing parameters, particularly infill percentage, in enhancing the mechanical performance and fatigue life of PLA gears. Their findings underscore the importance of parameter optimization to improve the durability of 3D-printed components, suggesting that a higher infill volume percentage significantly extends the lifespan of printed gears.

In parallel, Dimić *et al.,* [11] investigated the influence of material type on the performance of 3D-printed spur gears, concluding that PLA gears performed better than ABS gears in operational tests. The properties of PLA, such as reduced weight, wear resistance, and noise minimization—position it as an ideal material for 3D-printed gears in demanding environments. Zhang *et al.,* [12] extended this focus on parameter optimization, employing machine learning techniques to optimize printing parameters such as temperature, printing speed, and fill ratio. This optimization led to a threefold improvement in wear performance, highlighting the significant role that parameter settings play in enhancing the quality of 3D-printed gears. These studies demonstrate that careful control over printing parameters and material selection is crucial for achieving optimal performance in 3D-printed gears.

Further research by Pujari *et al.,* [13] provided a comprehensive review of 3D-printed spur gears, emphasizing design considerations and material selection. Their work addressed the importance of analyzing contact stress, tooth strength, and impact resistance, which are critical factors in the performance of gears. As the adoption of additive manufacturing continues to grow, the study underscores the need for in-depth evaluations of the mechanical characteristics of 3D-printed gears using both experimental and numerical methodologies. In a broader context, Tezel *et al.,* [14] conducted a comparative study on steel gears produced by additive and conventional manufacturing methods. Their findings revealed that gears produced by Direct Metal Laser Sintering (DMLS) exhibited density and hardness similar to those made by traditional engraving methods, suggesting that additive manufacturing can match conventional techniques in producing high-quality gears when proper post-production treatments are applied.

These studies illustrate the nature of 3D printing in gear manufacturing, highlighting the influence of material properties, printing parameters, and optimization techniques on the performance of the final products. While significant progress has been made in improving the quality and durability of 3D-printed gears, the research emphasizes the ongoing need for optimization in materials and manufacturing processes to realize the full potential of additive manufacturing in gear production. Table 1 summarizes the existing literature on 3D Printing Technology in Gear Manufacturing.

2.3 Dimensional Accuracy in 3D Printed Gears

The achievement of dimensional accuracy in 3D-printed gears has been a key focus in recent additive manufacturing research, mainly to understand how different materials and printing parameters influence the final product. Buj-Corral and Zayas-Figueras [1] compared two polymeric materials—PLA and Nylon-PA6—in the context of FFF 3D printed spur gears. Their study found that while PLA gears exhibited dimensional accuracy, Nylon gears, printed with a lower infill ratio, demonstrated fewer form errors. This suggests an inherent trade-off between material type and infill ratio must be carefully considered when designing 3D printed gears, as it can affect the final geometry and accuracy of the parts. This aligns with findings by Kotkar *et al.,* [15], who, while also investigating various polymers (ABS, PLA, Nylon 12), highlighted that infill percentage plays a crucial role in improving the load-bearing capacity of gears. These insights reveal that dimensional accuracy cannot be viewed in isolation but must be analyzed in conjunction with material choice and infill parameters to optimize the functional properties of the final product.

Tiwari and Kumar [16] explored how specific factors, such as the orientation and support effects, influence the dimensional accuracy of 3D printed parts made with PLA filament. Their findings underscore the importance of orientation in the FDM process, as gravity can impact the final accuracy, and the use of support features can further introduce variations. This study complements Buj-Corral and Zayas-Figueras [1] by identifying additional parameters, beyond material choice and infill ratio, that affect accuracy in FDM 3D printing. Furthermore, Kotliński *et al.,* [17] evaluated the geometry accuracy of gears produced by Selective Laser Sintering (SLS) and Multi-Jet Modeling (MJM) methods. Their findings revealed that the dimensional accuracy of gears produced using these methods was comparable but still inferior to that of traditional machining, with the accuracy falling within International Tolerance (IT) 12 or higher. These results reinforce the idea that while 3D printing methods such as SLS and MJM show promise, they still lag behind traditional machining processes to achieve high precision, which is crucial for gear applications.

Similarly, Glukchov *et al.,* [18] investigated the influence of layer structure and root formation on the quality of 3D-printed gears. They found that a thread network layer structure and forming the root of gears on the base circle could improve both the mechanical strength and geometric accuracy of the gears. This study adds to the growing body of work suggesting that innovative design techniques, such as modifying the internal structure and root formation of gears, can improve the accuracy and durability of 3D-printed gears. Tak *et al.,* [19], in their research on shrinkage during printing, emphasized that parameters such as scale, fill density, and solid layer significantly affect shrinkage and Dimensional discrepancies (Div) from design dimensions. Their study illustrates the critical role of printing parameters in achieving dimensional accuracy and minimizing distortions like shrinkage, which can compromise the functional performance of the gear.

These studies highlight that dimensional accuracy in 3D-printed gears is influenced by a combination of material selection, printing parameters (such as infill ratio and support structures), and printing technology (such as FDM, SLS, and MJM). While significant improvements have been made in enhancing accuracy, mainly through material optimization and the development of novel printing techniques, the studies suggest that 3D-printed gears still face challenges in matching the precision of gears produced by traditional manufacturing methods. Further exploration into advanced design modifications, optimization of printing parameters, and post-processing techniques is necessary to bridge this gap and enable 3D-printed gears to meet the stringent requirements of high-performance applications. Table 1 summarizes the existing literature on dimensional accuracy in 3D-printed gears.

Table 1
Summary of existing literature on Gear Manufacturing and 3D-printed gears

Author	Key focus	Material used	Findings	Key takeaways
Tak *et al.,* [19]	Shrinkage issues in 3D-printed parts	PLA	Investigated shrinkage and Div, finding that printing parameters like scale, fill density, and solid layers affect shrinkage.	Printing parameters significantly affect the dimensional accuracy of 3D-printed gears.
Kotkar *et al.,* [15]	Design and performance of 3D printed gears with various polymers	ABS, PLA, Nylon 12	Demonstrated the potential of 3D printing to produce complex gear designs, highlighting noise reduction and gear life extension.	Infill percentage plays a role in improving the load-bearing capacity of gears.
Tiwari and Kumar [16]	Factors affecting dimensional accuracy in 3D printing	PLA	Studied the effect of orientation and support features on the dimensional accuracy of FDM printed parts.	Orientation and support features influence dimensional accuracy in 3D printed parts.
Dimić *et al.,* [11]	Material impact on the operational behavior of 3D-printed gears	PLA, ABS	PLA gears outperformed ABS gears in operational characteristics such as wear and noise resistance.	PLA is a material for operational efficiency in 3D-printed gears.
Glukchov *et al.,* [18]	Improving mechanical strength and geometric accuracy	PLA	Enhancing the gear root formation on the base circle with thread network layer structure improved the quality of 3D printed gears.	Gear quality can be improved by optimizing root formation and layer structures.
Tezel *et al.,* [14]	Comparison of gears produced by additive vs. conventional methods	Steel, additive manufacturing materials	After surface treatment, additive manufacturing (DMLS) gears had similar density and hardness to conventionally produced steel gears.	Additive manufacturing can achieve gear characteristics comparable to traditional methods.

Zhang *et al.,* [12]	Optimization of printing parameters for gear performance	PLA, ABS, Nylon	Machine learning optimization of printing parameters resulted in a three-fold improvement in the wear performance of 3D-printed gears.	Optimized printing parameters significantly enhance gear wear performance.
Kotliński *et al.,* [17]	Geometry accuracy of 3D printed plastic gears	Plastic (SLS, MJM methods)	Found that 3D printing methods like SLS and MJM have manufacturing accuracy below that of traditional machining, with international tolerance IT 12 or higher.	SLS and MJM 3D printing methods offer accuracy but still fall short compared to traditional machining.
Hanon *et al.,* [9]	Dimensional accuracy in FDM-based 3D printing	PLA	High dimensional accuracy in 3D printed components, including gears, with commercial FDM printers.	FDM-based printers can produce highly accurate components for gear production.
Muminović *et al.,* [10]	Mechanical performance and durability of 3D printed gears	PLA	Increased infill percentage improved the fatigue life of 3D-printed PLA gears.	Infill percentage is crucial for enhancing the durability of 3D-printed gears.
Buj-Corral and Zayas-Figueras [1]	Dimensional accuracy comparison of PLA and Nylon-PA6 gears	PLA, Nylon-PA6	PLA gears showed better dimensional accuracy than Nylon-PA6 gears, but Nylon-PA6 with a lower infill ratio had fewer form errors.	Material type and infill ratio impact the dimensional accuracy and form error trade-offs.
Pujari et al. [13]	Review of 3D printed spur gears, focusing on design and evaluation	PLA, ABS, Nylon, and other polymers	Covers design, material selection, and methods for evaluating contact stress, tooth strength, and impact resistance.	A comprehensive review of design and material selection for 3D printed gears.

3. Methodology and Material

3.1 Material

Gears are integral in numerous industrial applications, ranging from textile machinery to aerospace systems. Their primary function is to facilitate efficient power transmission by modifying the rotational speed and torque of machine shafts. Gears are particularly advantageous in high-speed applications, such as automotive transmissions, due to their capacity to minimize energy loss while maintaining high precision. Small gears, in particular, enhance operational efficiency by offering high-speed ratios, reliability, and a compact design. However, the stress generated at the contact interface between gear teeth presents substantial mechanical challenges, particularly under high-load conditions.

PLA polymer is a commonly used material in 3D printing due to its biodegradability and user-friendly characteristics. PLA is considered environmentally sustainable and derived from renewable sources such as cornstarch or sugarcane. As presented in Table 2, it is non-toxic and safe for indoor use, with a melting point ranging from 180°C to 220°C, making it compatible with most consumer-grade 3D printers.

Although PLA exhibits adequate tensile strength and toughness for many applications, its lower heat resistance and tendency to deform under prolonged compression make it less suitable for high-stress scenarios. Nevertheless, PLA remains a viable material choice for 3D-printed gears under moderate loading conditions. For this study, PLA was selected for gear production due to its ease of use and potential for property enhancement through post-processing techniques, such as annealing.

Table 2
Properties of PLA Polymer

Property	Value
Density	~1.25 g/cm³
Melting point	180–220°C
Tensile strength	50–70 MPa
Biodegradability	Yes

3.2 Design of Experiments

In this study, the Taguchi Method was used to optimize 3D printing parameters to improve the dimensional accuracy of PLA spur gears. The Taguchi method allows for the efficient evaluation of process parameters with a reduced number of experiments. It employs orthogonal arrays to assess multiple factors simultaneously, minimizing the experimental cost and complexity while ensuring optimal results. This study used an L9 orthogonal array (OA) to investigate the effect of three key 3D printing parameters: layer thickness, infill, and printing speed. These specific levels were chosen to reflect typical ranges used in PLA printing. A thinner layer thickness can lead to higher resolution but longer print time, while higher infill density increases part strength at the cost of material and time. Printing speed influences the deposition quality and bonding between layers. The selected levels ensured a comprehensive representation of both low, medium, and high values for each parameter.

RSM was also employed to analyze the interactions between these parameters and to develop a predictive model. Using MINITAB software (version 18), statistical analysis was conducted through analysis of variance (ANOVA) to establish the significance of each parameter and to determine the optimal conditions for minimal Div [22]. The experimental setup and the abbreviations of printing parameters and output responses are outlined in Tables 3 and 4.

Table 3
Printing parameters and output response abbreviations

Printing parameter	Abbreviations	Units
Layer Thickness	A	Count
Infill	B	%
Printing Speed	C	mm/second
Dimensional Deviation	Div	Millimeter (mm)

Table 4
Printing parameters and their levels

Input Parameters	Units	Coded Levels	Actual Values
Layer Thickness	Count	-1, 0, 1	0.12, 0.15, 018
Infill	%	-1, 0, 1	88, 92, 96
Printing Speed	mm/second	-1, 0, 1	15, 24, 33

To minimize the number of experiments while still exploring the interaction effects between multiple parameters, the Taguchi design of experiments (DOE) approach was adopted. Specifically, the L9 (3^3) orthogonal array was selected, which accommodates three parameters each at three levels, resulting in just nine experimental runs. The L9 array was chosen for its efficiency and suitability in screening the main effects of factors with a reduced number of trials, thus conserving material and time without compromising the integrity of the analysis. This design allows for an initial optimization and identification of the most influential factor with statistical reliability. Moreover, the L9 design supports subsequent modeling using response surface methodology (RSM) for more refined analysis. The Taguchi L9 design and coded levels of input parameters for the experiments are presented in Table 5. The table shows the coded and actual values of the layer thickness, infill, and printing speed used for each experimental run.

Table 5
Taguchi level design for input parameters

Run Order	A Coded	An Actual	B Coded	B Actual	C Coded	C Actual
1	-1	0.12	-1	88	-1	15
2	-1	0.12	1	92	1	24
3	-1	0.12	+1	96	+1	33
4	1	0.15	-1	88	1	24
5	1	0.15	1	92	+1	33
6	1	0.15	+1	96	-1	15
7	+1	0.18	-1	88	+1	33
8	+1	0.18	1	92	-1	15
9	+1	0.18	+1	96	1	24

3.3 Experimental Setup

The 3D printing of PLA spur gears was conducted using an Ender 6 low-cost polymer 3D printer. The design of the gears was done in SOLIDWORKS and exported as STL files to the Ultimaker Cura 4.13.0 software for slicing. Each gear had a diameter of 40 mm, and nine gears were printed based on the Taguchi L9 experimental design. The specifications of the Ender 6 printer are provided in Table 6, highlighting its compatibility with PLA and its performance in printing gears with precise dimensional accuracy. The nozzle diameter was set to 0.04 mm in all experiments to ensure consistency across all printed gears. Figure 1 shows the Ender 6 printer used in the experiment.

Table 6
Ender 6 Printer Specifications

Property	Description
Build Volume	250mm x 250mm x 400mm
Layer Resolution	0.05mm
Print Speed	Up to 150 mm/s
Filament Compatibility	PLA, ABS, PETG
Connectivity	USB, SD card
Print Bed	Heated, Glass
Supported File Formats	.STL, .OBJ
Control Interface	Touchscreen

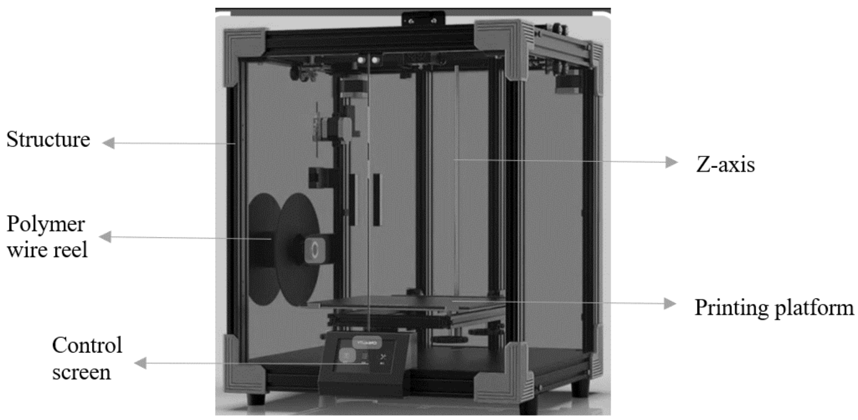

Fig. 1. Ender 6 printer

3.4 Output response measurement

Dimensional accuracy is a critical factor in the performance of 3D-printed components, especially gears, where even slight deviations from the intended geometry can significantly impact their functionality. Achieving high precision in 3D printing is influenced by multiple factors, including the printing technology used, the postprocessing techniques applied, the use of support materials, and the orientation of the object during the printing process.

In this study, the dimensional accuracy of the printed PLA spur gears was evaluated using a Smart Optics Vinyl Scanner, capable of achieving a scanning precision of 0.4 µm. The scanned data assessed how closely the printed gears matched their original CAD models. Figure 2 illustrates the process of gear scanning using the Smart Optics Vinyl Scanner, while Figure 3 displays the nine scanned gears produced under different experimental conditions.

Fig. 2. Gear scanning using Smart Optics Vinyl Scanner

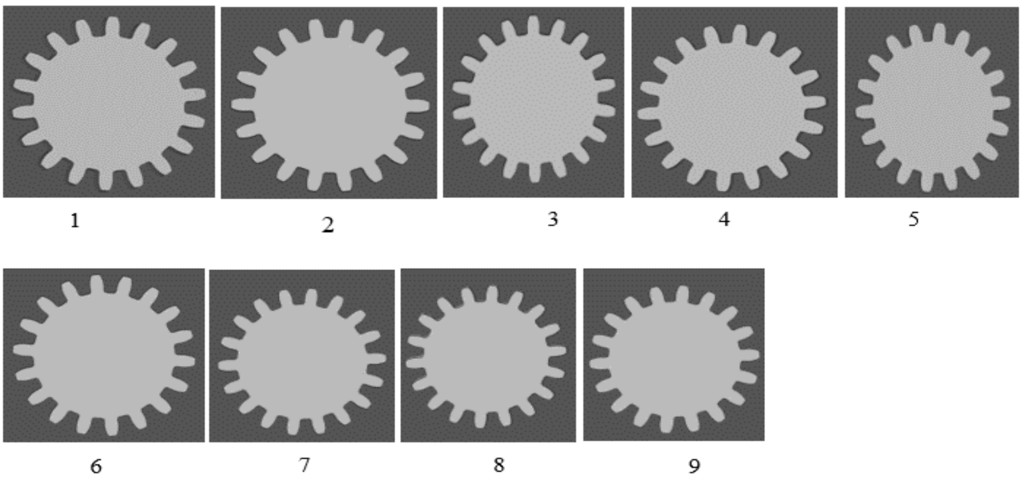

Fig. 3. Nine scanned gears for different sets of parameters

To accurately measure the geometric accuracy of the printed gears, GOM 3D Inspection Software 2022 was employed. This software allows for a precise comparison between the scanned 3D model and the original CAD design created in SOLIDWORKS. The measured dimensional variance provided insight into the deviation of each gear from its intended geometry, helping to determine the optimal set of printing parameters for achieving the highest dimensional accuracy.

The process of dimension measurement began by connecting the Smart Optics Vinyl Scanner to the EXOCAD 3.0 Galway 2021 software, which facilitated viewing and saving the scan data in STL format. This STL data was then imported into GOM 3D Inspection Software for dimensional analysis. The first step in the software involved aligning the scanned mesh (representing the actual printed part) with the CAD model to ensure an accurate comparison. The alignment procedure, combined with precise measurements of key dimensions such as the diameter, tooth width, and root clearance, allowed for a comprehensive analysis of the dimensional fidelity of the gear. Figure 4 outlines the steps in using GOM 3D inspection software to measure dimensional accuracy, including mesh alignment, comparison, and reporting of Div.

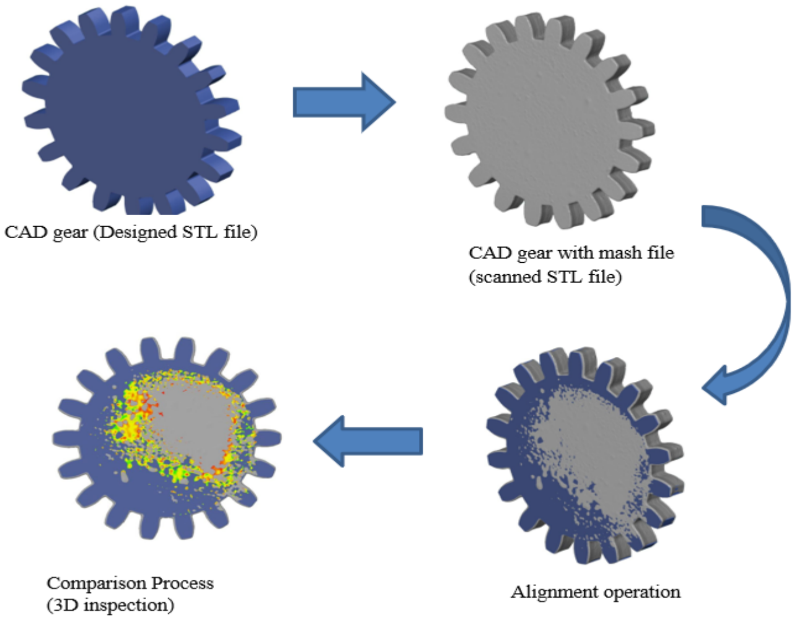

Fig. 4. GOM 3D inspection software dimensional measuring steps

4. Result

The dimensional accuracy of the printed gears is evaluated by comparing the CAD model with the actual SLA printouts. The primary method of comparison involved using GOM 3D inspection software to generate color maps that highlight deviations in millimeters. These deviations represent dimensional discrepancies between the CAD model and the printed gear. Positive values indicate an excess in the printed material, while negative values show a deficit in the printed profile. Figure 5 presents the color map for one of the nine gears, reflecting the dimensional variation.

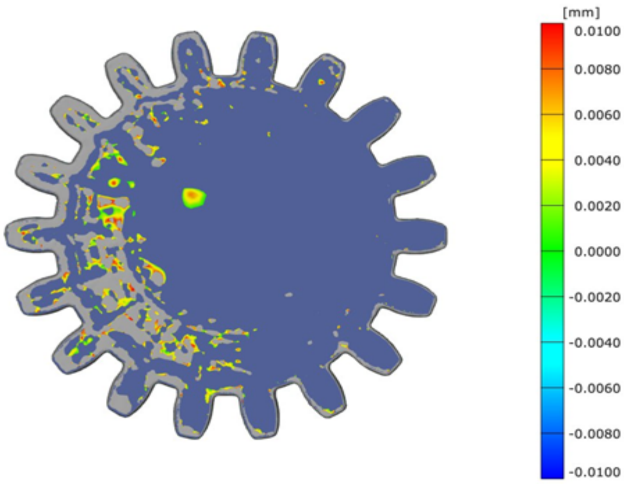

Fig. 5. Comparison between the CAD model and the SLA-printed version of the gear

Each gear was printed using a unique set of parameters, and the results were measured accordingly. Table 7 outlines the Div for each experiment, where the gears were printed according to a three-level Taguchi L9 design.

Table 7
Average response results

No	A (count)	B (%)	C (mm/s)	Div (mm)
1	0.12	88	15	0.018685259
2	0.12	92	24	0.026626984
3	0.12	96	33	0.046324111
4	0.15	88	24	0.025099602
5	0.15	92	33	0.047859922
6	0.15	96	15	0.019880478
7	0.18	88	33	0.079011858
8	0.18	92	15	0.020116279
9	0.18	96	24	0.052851563

4.1 Dimensional Deviation Analysis

Div is critical to the success of stereolithography (SLA) due to their impact on the accuracy of the final printed product. The color maps generated by GOM 3D inspection software illustrate deviations from the CAD model, highlighting areas where the printed components exceeded or fell short of the intended geometry. These deviations provide a quantitative insight into the performance of the printing process.

Using Minitab software, quadratic regression models were created to represent the relationship between printing parameters and dimensional accuracy. These models exhibited a high degree of fit, as reflected by the high R-squared (R^2), adjusted R-squared (R^2adj), and predicted R-squared (R^2pred) values, which all confirmed the robustness of the model, as shown in Table 8. ANOVA tests revealed that speed (C) was the most significant parameter, while layer thickness (A) and infill (B) had lesser impacts. The analysis was conducted at a 95% confidence interval, with significant process parameters exhibiting a P-value ≤ 0.05. From the ANOVA results, speed was observed to have the most substantial influence on Div, with a P-value of 0.090, indicating near-significance. In contrast, layer thickness and infill had higher P-values, meaning their impact on Div was less critical. The final regression equation for the Div is shown in Equation 1. This equation illustrates the effect of each parameter on the dimensional accuracy of the printed parts.

$$Div\ (mm) = -0.049 + 0.335\ (Layer) - 0.00016\ (Infill) + 0.002121\ (Speed) \quad (1)$$

Table 8
ANOVA result

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Layer	2	0.000793	0.000793	0.000397	3.63	0.216
Infill	2	0.000156	0.000156	0.000078	0.71	0.583
Speed	2	0.002214	0.002214	0.001107	10.13	0.090
Residual Error	2	0.000219	0.000219	0.000109		
Total	8	0.003383				

4.2 Main Effects Plot

The Main Effects Plot for Means in Figure 6 indicates that layer thickness and speed significantly impact dimensional accuracy, while the effect of infill percentage is less pronounced. As the layer thickness increases from 0.12 to 0.18, Div consistently rises, suggesting that thinner layers improve accuracy. For infill percentage, the increase from 88% to 96% shows a slight rise in Div, indicating a minor impact on accuracy. Speed demonstrates the most significant effect, with the Div being lowest at a speed of 24 mm/s. Accuracy is reduced at lower speeds (15 mm/s), while higher speeds (33 mm/s) result in a sharp increase in Div, suggesting an optimal speed near 24 mm/s for minimizing errors. This highlights that reducing layer thickness and selecting the optimal speed is critical for enhancing 3D printing accuracy.

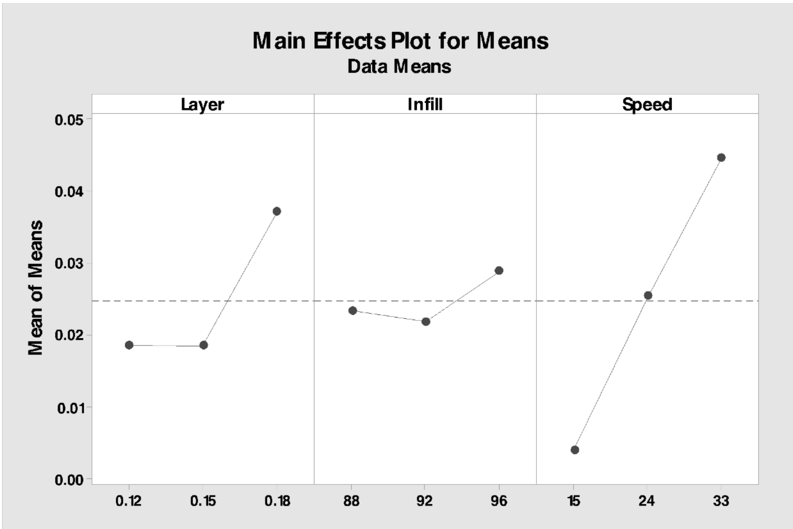

Fig. 6. The main effect plots

4.3 Optimization of Response

Achieving optimal responses is essential for meeting specific objectives in complex systems, such as 3D printing processes. This study employed multi-response optimization to identify the best combination of process parameters—layer thickness, infill percentage, and printing speed—for minimizing Div. Unlike single-objective optimization, which provides a single optimal solution, multi-response optimization generates multiple solutions that are considered optimal depending on the context. The primary objective was to minimize Div, represented by the optimization equation in Equation 2.

Minimize (Div) = f (layer, infill, speed) (2)

Given the complexity and interdependence of process variables, determining the ideal parameter configuration was challenging. The optimization focused on the main effects of the parameters, as revealed in the Main Effects Plot (Figure 6). A parametric optimization approach was used, assigning significance to each parameter. Printing speed (C) was identified as the most influential parameter, with the highest significance value of 15, followed by layer thickness (A) with a significance of 0.12, and infill percentage (B) with a significance of 92%. Weighting factors were also incorporated to adjust the sensitivity of the optimization process toward achieving the desired output, with a moderate sensitivity level applied to balance precision and practicality.

The Minitab Response Optimizer tool was utilized to determine the optimal parameter configuration and provide a compromise between various responses. The optimization goals and constraints are summarized in Table 9, where the input parameters (layer thickness, infill percentage, and speed) were kept within specified ranges, and the Div was minimized to a target value of 0.0182209 mm.

Table 9
Goals and Constraints for Inputs and Responses

Parameter/response	Goal	Lower Limit
Layer, A	In range	0.15
Infill, B	In range	92
Speed, C	In range	15
Div	Minimize	0.0182209

5. Discussion

The results of the dimensional accuracy analysis of 3D-printed spur gears provide valuable insights into how printing parameters impact the final printed part. Dimensional discrepancies were evaluated by comparing the actual SLA printouts with the CAD model, revealing deviations in millimeters (Div) that highlight areas where the printed gear either exceeded or fell short of the intended dimensions. Positive deviations indicated overprinting of material, while negative deviations represented under-printing. The GOM 3D inspection software allowed for detailed color maps, which visually represented these variations, with some areas of the gear printing with excellent accuracy, while others showed significant discrepancies. These findings align with previous studies that emphasize the criticality of identifying and mitigating dimensional deviations in additive manufacturing to improve accuracy and reliability [20].

The Taguchi L9 experimental design systematically investigated the impact of three printing parameters: layer thickness (A), infill percentage (B), and speed (C). Each parameter was varied across three levels, and the corresponding Div was measured, as summarized in Table 8. The results showed that Div varied considerably across different parameter combinations, providing critical information on the relationship between the printing parameters and the final print accuracy. The ANOVA results indicated that printing speed (C) had the most significant effect on dimensional accuracy, with a near-significant P-value of 0.090. This suggests that changes in printing speed could substantially affect the final geometry of the printed gear. In contrast, the higher P-values for layer thickness (A) and infill percentage (B) indicated that these parameters had a lesser impact on dimensional accuracy than printing speed. Similar conclusions were drawn in research by Khosravani *et al.,* [21], who found that printing speed consistently influenced geometric precision across various additive manufacturing applications.

The regression model formulated to express the relationship between the parameters and Div (Equation 1) demonstrated a high degree of fit with higher R^2 values. This model confirmed the primary influence of speed on Div, with a minor effect from infill percentage. The Main Effects Plot confirmed these findings, with Div increasing sharply as speed increased from 15 mm/s to 33 mm/s. Lower speeds, around 24 mm/s, appeared to produce the best results with minimal deviation, while thinner layers (0.12 mm) consistently produced better accuracy, suggesting that delicate layers contribute to more precise printing.

The multi-response optimization process aimed to minimize Div by adjusting the printing parameters. Using the Minitab Response Optimizer tool, the optimal combination for minimizing Div was a layer thickness of 0.15 mm, an infill percentage of 92%, and a printing speed of 24 mm/s. These results align with the Main Effects Plot, which showed that a printing speed of 24 mm/s and thinner layers contribute to improved dimensional accuracy. This optimization process highlighted the importance of controlling speed and layer thickness when aiming for high dimensional accuracy in SLA 3D printing.

6. Conclusions

This study provides significant insights into the key printing parameters that influence the dimensional accuracy of SLA 3D printed gears. By systematically investigating the impact of layer thickness, infill percentage, and printing speed on the final geometry of the printed gears, the study has highlighted the critical role of printing speed in achieving high precision. The regression models and ANOVA results demonstrated that speed had the most significant effect on dimensional accuracy, with optimal results observed at a printing speed of 24 mm/s, and thinner layers (0.12 mm) also contributed to better dimensional consistency, reinforcing the importance of careful parameter selection when aiming for high-quality 3D prints.

The optimization process used multi-response optimization techniques and further refined the parameter combinations to minimize Div. The optimal configuration, consisting of a layer thickness of 0.15 mm, an infill percentage of 92%, and a printing speed of 24 mm/s, offered the best balance between precision and practicality. This optimization enhances the quality and accuracy of printed parts and contributes to a more efficient 3D printing process, ultimately reducing material waste and improving production time. Such improvements can be crucial for industries that require highly functional and accurate parts, including automotive, aerospace, and medical device manufacturing. The findings of this study are highly relevant to industries where precision is paramount, such as the production of gears and other mechanical components, which require tight tolerances and high operational efficiency. The ability to optimize 3D printing parameters for dimensional accuracy is a valuable tool for improving the reliability and performance of end-use parts. The findings can also be applied to various sectors, including automotive, where gears play a critical role in power transmission, and medical device manufacturing, where high-precision parts are essential for functionality and safety.

This study offers practical benefits for improving 3D printing of functional polymer parts. Optimizing the process parameters enhances dimensional accuracy, reducing the need for post-processing and minimizing material waste. Improved accuracy also ensures better gear performance and durability. The optimized settings balance print quality and speed, increasing overall process efficiency. These results are particularly relevant for precision applications in medical devices, robotics, and automotive prototypes requiring lightweight and biodegradable components.

Despite the positive outcomes, this study has certain limitations. The analysis was limited to three printing parameters—layer thickness, infill density, and printing speed—while other influential factors such as nozzle temperature, build orientation, and cooling rate were not considered. Additionally, the findings are specific to PLA material and may not directly apply to other polymers.

This research opens the door for future studies to explore additional factors that could influence the dimensional accuracy of SLA 3D printed parts. Variables such as resin properties, curing times, and temperature control could all play essential roles in the final print quality. Post-processing methods, including annealing or surface finishing techniques, may also be investigated to enhance further the dimensional accuracy and overall mechanical properties of printed parts. These future research avenues promise to refine the 3D printing process, making it even more adaptable and effective in producing parts with complex geometries and functional requirements.

This study contributes to a deeper understanding of SLA 3D printing technology and provides practical recommendations for improving the dimensional accuracy of printed gears. By optimizing printing parameters and exploring additional influencing factors, it is possible to enhance the overall quality, performance, and cost-effectiveness of 3D printed parts, thus expanding the potential applications of SLA 3D printing across diverse industries.

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References

[1] Buj-Corral, Irene, and Enrique Ernesto Zayas-Figueras. "Comparative study about dimensional accuracy and form errors of FFF printed spur gears using PLA and Nylon." *Polymer Testing* 117 (2023): 107862. https://doi.org/10.1016/j.polymertesting.2022.107862

[2] Harsha, K. Mohan, and Y. Seetharama Rao. "Comparison of wear behaviour of polymer spur gears using FDM process." *In IOP Conference Series: Materials Science and Engineering*, vol. 1168, no. 1, p. 012028. IOP Publishing, 2021. https://doi.org/10.1088/1757-899x/1168/1/012028

[3] Ciobanu, Robert, Ciprian Ion Rizescu, Dana Rizescu, and Bogdan Gramescu. "Surface Durability of 3D-Printed Polymer Gears." *Applied Sciences* 14, no. 6 (2024): 2531. https://doi.org/10.3390/app14062531

[4] Fekete, Gusztáv. "Numerical wear analysis of a PLA-made spur gear pair as a function of friction coefficient and temperature." *Coatings* 11, no. 4 (2021): 409. https://doi.org/10.3390/coatings11040409

[5] Ghazali, Wafiuddin Md, Daing Mohamad Nafiz Daing Idris, Azizul Helmi Sofian, Januar Parlaungan Siregar, and Ismail Ali Abdul Aziz. "A review on failure characteristics of polymer gear." *In MATEC Web of Conferences, vol. 90, p. 01029. EDP Sciences*, 2017. https://doi.org/10.1051/matecconf/20179001029

[6] Kolia, Tushar, Arajpureb, V.G., and Patilc, V.H. "Design and analysis of different polymer gears in feed drive mechanism for all geared Lathe machine." *International Journal of Mechanical Engineering*, vol.6, no.3 (2021): 3406.

[7] Kuo, Chil-Chyuan, Ding-Yang Li, Zhe-Chi Lin, and Zhong-Fu Kang. "Characterizations of polymer gears fabricated by differential pressure vacuum casting and fused deposition modeling." *Polymers* 13, no. 23 (2021): 4126. https://doi.org/10.3390/polym13234126

[8] Hlebanja, Gorazd, Matija Hriberšek, Miha Erjavec, and Simon Kulovec. "Durability Investigation of plastic gears." *In MATEC Web of Conferences,* vol. 287, p. 02003. EDP Sciences, 2019. https://doi.org/10.1051/matecconf/201928702003

[9] Hanon, Muammel M., László Zsidai, and Quanjin Ma. "Accuracy investigation of 3D printed PLA with various process parameters and different colors." *Materials Today: Proceedings* 42 (2021): 3089-3096. https://doi.org/10.1016/j.matpr.2020.12.1246

[10] Muminović, Adis J., Sanjin Braut, Željko Božić, Nedim Pervan, and Ante Skoblar. "Experimental failure analysis of polylactic acid gears made by additive manufacturing." *Procedia Structural Integrity* 46 (2023): 125-130. https://doi.org/10.1016/j.prostr.2023.06.021

[11] Dimić, Aleksandar, Žarko Mišković, Radivoje Mitrović, Mileta Ristivojević, Zoran Stamenić, Jan Danko, Jozef Bucha, and Tomáš Milesich. "The influence of material on the operational characteristics of spur gears manufactured by the 3D printing technology." *Strojnícky časopis-Journal of Mechanical Engineering* 68, no. 3 (2018): 261-270. https://doi.org/10.2478/scjme-2018-0039

[12] Zhang, Ye, Ken Mao, Simon Leigh, Akeel Shah, Zhiming Chao, and Guotao Ma. "A parametric study of 3D printed polymer gears." *The International Journal of Advanced Manufacturing Technology* 107 (2020): 4481-4492. https://doi.org/10.1007/s00170-020-05270-5

[13] Pujari, Likhith, S. Manoj, Omkar K. Gaddikeri, Pranam Shetty, and Mantesh B. Khot. "Recent advancements in 3D printing for gear design and analysis: A comprehensive review." *Multiscale and Multidisciplinary Modeling, Experiments and Design* (2024): 1-25. https://doi.org/10.1007/s41939-024-00529-w

[14] Tezel, Tugce, Eyup Sabri Topal, and Volkan Kovan. "Failure analysis of 3D-printed steel gears." *Engineering Failure* Analysis 110 (2020): 104411. https://doi.org/10.1016/j.engfailanal.2020.104411

[15] Kotkar, Tanmay, Prashant Masure, Pundalik Modake, Chirag Lad, and Basanagouda Patil. "Modelling and testing of spur gear made of different 3D printed materials." *Int. JS Res. Sci. Eng* 4 (2018): 1389-1394.

[16] Tiwari, Kushagra, and Santosh Kumar. "Analysis of the factors affecting the dimensional accuracy of 3D printed products." *Materials Today: Proceedings* 5, no. 9 (2018): 18674-18680. https://doi.org/10.1016/j.matpr.2018.06.213

[17] Kotliński, Jarosław Piotr, Karol Łukasz Osowski, Zbigniew Kęsy, and Andrzej Kęsy. "Accuracy of Geometry of Plastic Gear Produced with 3D Printing Technology." *International Review of Mechanical Engineering (IREME)* 14, no. 7 (2020). https://doi.org/10.15866/ireme.v14i7.18380

[18] Glukchov, V. I., L. G. Varepo, I. V. Nagornova, and F. A. Doronin. "Strength and geometry parameters accuracy improvement of 3D-printed polymer gears." *In Journal of Physics: Conference Series,* vol. 1260, no. 3, p. 032019. IOP Publishing, 2019. https://doi.org/10.1088/1742-6596/1260/3/032019

[19] Tak, A., Ingavale, P., Khopatkar, C., Bhure, S., Barve, V., & Rajurkar, A. "Effect of 3D Printing Parameters on Dimensional Accuracy & Shrinkage on Printed Parts." *National Conference on Modeling, Optimization and Control, NCMOC.* (2015).

[20] Singh, Shamsher, Abhas Jain, Prachi Chaudhary, Rishabh Gupta, and Harlal Singh Mali. "Optimization of dimensional accuracy and surface roughness in m-SLA using response surface methodology." *Rapid Prototyping Journal* 29, no. 6 (2023): 1324-1339. https://doi.org/10.1108/RPJ-05-2022-0158

[21] Khosravani, Mohammad Reza, Filippo Berto, Majid R. Ayatollahi, and Tamara Reinicke. "Characterization of 3D-printed PLA parts with different raster orientations and printing speeds." *Scientific Reports* 12, no. 1 (2022): 1016. https://doi.org/10.1038/s41598-022-05005-4

[22] Abd Aziz, Mohamad Redhwan, Arifuddin Ariffin, A. M. Syafiq, Zainal Ariffin Selamat, and A. R. M. Aminullah. "Effect of Significant Machining Parameters Towards Turning Cutting Performance." Journal of Advanced Research Design 113, no. 1 (2024): 1-10. https://doi.org/10.37934/ard.113.1.110