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Original Article

Fused deposition modeling (FDM) process parameter optimization for PLA component manufacturing

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ABSTRACT

Technological developments in manufacturing have significantly improved living standards in recent years. These advancements are largely driven by progress in material science and the development of manufacturing techniques that enable cost-effective mass production. Additive manufacturing (AM) is a production method that creates objects by adding material layer by layer based on three-dimensional model data. In this process, a physical product is generated directly from a 3D Computer-Aided Design (CAD) model. The main objective of additive manufacturing technologies is to produce components with minimal cost, high quality, and optimal efficiency. In this study, the effects of process parameters on the strength, filament consumption, and printing time of PLA (Polylactic Acid) parts produced by Fused Deposition Modelling (FDM) were investigated. The produced parts were 'Clip Control Fixtures (CCF)' used to check the presence of clips on wire harness bundles manufactured at YAZAKI. Wall line count (WLC), infill density (ID), and print speed (PS) were selected as process parameters. Experiments were conducted using the Taguchi L9 experimental design with three levels for each factor. According to the analysis performed under the "larger is better" assumption, WLC had the greatest effect on strength 56.21%, followed by ID 33.49%. The optimal parameter combination for maximum strength was determined as WLC 6, ID 90, and PS 40. For filament consumption "smaller is better", ID showed the highest influence 95.68%. For printing time, PS 71.53% and ID 27.71% were the most influential factors, and the optimal combination was WLC 2, ID 20, PS 120.

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INTRODUCTION

Fused deposition modelling (FDM) is one of the most widely used additive manufacturing (AM) techniques because of its accessibility, relatively low cost, and compatibility with various thermoplastic materials such as polylactic acid (PLA). Despite its advantages, the mechanical performance, material consumption, and production time of FDM-printed parts are strongly influenced by process parameters. Therefore, finding relationships and optimization of these parameters is essential to achieve components with adequate strength, reduced material usage, and efficient production.

In industrial applications, particularly in the automotive sector, fixtures produced by AM method can play an important role in inspection and assembly processes. In

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this context, this study focuses on the finding of optimization proportion criteria of process parameters to produce PLA-based CCF used to verify the presence of clips on wire harness bundles manufactured at YAZAKI. WLC, ID, and PS were selected as key process parameters and investigated using the Taguchi L9 experimental design.

Numerous studies in the literature on FDM methodology indicate that process parameters have significant individual effects on production time, filament consumption, and the mechanical strength of printed parts. In particular, the selection of G-code parameters is considered a critical factor in the manufacturing process. Several studies have investigated the influence of G-code parameters on PLA, a sustainable thermoplastic polyester widely used in FDM technology due to its biodegradability, ease of printing, and relatively good mechanical properties. These parameters, however, may also vary depending on the specific filament type used in the printing process. A review of the literature shows that the generated G-code is strongly influenced by parameters such as wall line count, infill density, layer height, and print speed [1]. These parameters have been identified as some of the most influential factors in determining the final performance, material usage, and production efficiency of FDM-printed components.

In a study conducted by Mazlan and Anas, the effects of infill density, wall perimeter, and layer height on the manufacturing performance of 3D printed parts were investigated [1]. The study revealed that the quality and mechanical performance of 3D printed components are influenced not only by the material used but also by specific printing parameters. Both computational analysis and experimental results demonstrated that increasing the values of the three parameters wall perimeter, infill density, and layer height can lead to an improvement in the tensile flexibility of the printed component. It was also concluded that reducing the infill density decreases the cross-sectional area of the structure, which may result in a smaller load-bearing surface area required to maintain structural integrity. Furthermore, increasing the layer height was found to reduce the total printing time; however, this improvement in production efficiency may lead to a rougher and less uniform surface texture in the printed part. These findings highlight the importance of optimizing key printing parameters to balance mechanical performance, production efficiency, and surface quality in FDM-based AM processes.

Furthermore, various other factors can also influence the mechanical properties of FDM-printed components. Lee and Yin conducted a study to investigate the effect of compressed air cooling in a PLA-based FDM 3D printing process [2]. The authors proposed the development of a novel autonomous compressed air-cooling system integrated with the print head. In this system, the airflow direction is controlled through an adjustable fan speed mechanism to directly cool the extruded material during the printing process. This approach also provides improved environmental stability within the printing chamber by facilitating air circulation. The experiments were conducted under constant printing conditions, including 100% infill density, a build platform temperature of 45°C, a nozzle temperature of 210°C, and a printing speed of 30 mm/s. According to the findings of the study, an inverse relationship was observed between the cooling air flow rate and both the dimensional accuracy and mechanical strength of the printed parts. Increasing the airflow rate improved the dimensional quality of the printed components; however, it resulted in a reduction in their mechanical strength. These results indicate that cooling conditions play a significant role in determining the final mechanical and dimensional performance of FDM-produced parts.

Another related study conducted by Yu carries out investigation and examining the effects of layer height, infill density, and print speed on the tensile and compressive properties of PLA materials [3]. In this research, an orthogonal experimental design was employed to effectively minimize the number of required tests while maintaining reliable analytical results. The parameters included variable layer heights (0.15 mm, 0.20 mm, 0.25 mm, and 0.30 mm), infill densities (40%, 60%, 80%, and 100%), and print speeds (30 mm/s, 40 mm/s, 50 mm/s, and 60 mm/s). A total of 16 experiments were conducted using different combinations of these manufacturing parameters. The results of the study indicated that layer height had the most significant influence on the tensile strength of the printed components. However, the G-code parameter settings in this approach were not adequate for the effect of other parameters for output variables.

Unlike the previously mentioned studies, Kartal investigated the effects of surface roughness on PLA material by considering parameters such as bed temperature, nozzle temperature, and layer height using the Taguchi optimization approach [4]. In this study, a Taguchi L9 experimental design was employed, where cubic specimens were printed and their surface roughness values were subsequently measured. During the analysis, the "smaller is better" criterion was adopted, and the average surface roughness value was selected as the response parameter. According to the findings of the study, nozzle temperature was identified as the most influential parameter with an effect ratio of 86.85%, followed by layer height with 7.1% and bed temperature with 5.9%. Based on the experimental results, the author concluded that the optimal parameter combination for improving dimensional accuracy and reducing surface roughness consisted of a bed temperature of 50°C, a nozzle temperature of 230°C, and a layer height of 200 μm. However, it was also emphasized that these parameter settings may not be universally applicable to other 3D printers due to temperature fluctuations within the printer chamber, which can influence the thermal stability of the printing process. In addition to the analysis above, AM technology enables the production of complex prototype components by adjusting various process parameters such as PS, temperature, infill pattern and other printing conditions. Also, the effectiveness of standard G-code parameters, FDM technology also provides the option to select different infill patterns, which can significantly influence the mechanical behavior of printed parts. In this context, Tran conducted a study to investigate how the selection of infill patterns and layer thickness affects the mechanical strength of PLA materials in 3D printing processes [5]. In this research, nine experimental configurations were evaluated using the Taguchi L9 experimental design. The study considered three different infill patterns zigzag, triangular, and grid as well as three-layer thickness values (0.20 mm, 0.10 mm, and 0.15 mm) as the primary process variables. In total, 27 tensile test specimens were produced in accordance with the ASTM D638 Type IV standard, with three replicates for each experimental condition. The results indicated that the triangular infill pattern provided the highest mechanical strength among the tested configurations, while the zigzag infill pattern resulted in the lowest mechanical performance. These findings demonstrate that the selection of infill pattern and layer thickness plays an important role in determining the mechanical properties of PLA components manufactured using FDM technology.

The performance and efficiency of components produced by 3D printing technologies are strongly influenced by process related factors such as mechanical strength, printing time, and filament consumption. These parameters are critical not only for ensuring structural integrity but also for achieving cost-effective and time-efficient manufacturing. Despite extensive research on FDM-printed PLA parts, existing studies predominantly focus on standardized test specimens and often evaluate performance metrics individually, rather than considering functional components.

However, industrial applications such as CCF require simultaneous consideration of both mechanical performance and production efficiency. In particular, the combined effects of WLC, ID, and PS, especially the role of WLC in load-bearing behavior have not been sufficiently investigated for such applications. Furthermore, achieving a balance between tensile strength, production time, and material consumption remains a key challenge in functional component design.

To address this gap, the present study focuses on the optimization of WLC, ID, and PS parameters for CCF applications using the Taguchi method. Unlike conventional approaches, this work evaluates multiple performance outputs, including mechanical strength, production time, and filament consumption, within a unified framework to identify the most efficient parameter combination. By targeting functional CCF components rather than relying solely on standardized specimens, this study provides a practical and application-oriented contribution to the field. The results offer actionable insights into in-house production and support the development of optimized AM strategies for industrial fixture design.

The main contribution of this study lies in revealing the critical influence of WLC on the mechanical performance of functional CCF components, while simultaneously considering production related outputs within a unified evaluation approach.

FDM 3D Printing Process Workflow

The steps involved in the 3D printing process can be defined sequentially as follows. First, the three-dimensional model of the object to be produced is designed and digitally generated using CAD software or obtained through 3D scanning. The created or scanned model is then converted into a file format suitable for slicing software and saved accordingly. In the next stage, the G-code parameters required for the manufacturing process such as material type, layer thickness, ID, and printing temperature are determined. The model is subsequently processed in the slicing software, where it is divided into layers and the corresponding G-code instructions are generated.

The generated G-code is then transferred to the 3D printer. After the printer is prepared for operation, the printing process is initiated, and the physical object is produced layer by layer. Finally, the printed object is removed from the printer, support structures are cleaned if present, and necessary post-processing operations are applied to obtain the final product.

G-Code Structure and Its Importance in AM

G-code is a programming language consisting of G and M commands that define machine movements and operations in AM systems. It is automatically generated by slicing software during the conversion of digital models into printable formats and serves as the instruction set guiding the 3D printing process. Acting as a bridge between digital design and physical production, G-code controls key parameters such as toolpath, movement speed, and material extrusion. Furthermore, a fundamental understanding of G-code enables enhanced process control, allowing users to optimize printing performance and effectively troubleshoot potential issues.

The Effects of G-Code Parameters

Wall line count

WLC, also referred to as the number of perimeters or outer walls, is an important parameter in FDM 3D printing that directly affects the structural strength and durability of printed components. This parameter determines how many solid contour lines are printed around the outer boundary of each layer. Increasing the WLC results in thicker outer shells, which can significantly improve the mechanical strength, stiffness, and overall structural integrity of the printed part. In many cases, higher WLC contributes more to the mechanical performance of a component than ID, since the outer walls typically bear a greater portion of the applied loads. However, increasing the number of wall lines also leads to higher material consumption and longer printing times. Therefore, selecting an appropriate WLC is essential to balance mechanical performance, material efficiency, and production time in FDM manufacturing processes.

Print speed

Studies examining the effect of PS on FDM-printed PLA samples have shown that increasing the PS can negatively affect several mechanical and physical properties of the printed components. It has been reported that an increase in PS leads to a reduction in mass, top surface hardness, and tensile strength, while simultaneously increasing the porosity of the printed structure. In addition, the effective Young's modulus of PLA material decreases after printing, and this reduction becomes more pronounced as the printing speed increases [6]. These findings indicate that PS plays a critical role in determining the mechanical performance and structural integrity of FDM-produced parts.

Cooling fan

The dimensional quality and mechanical properties of FDM-printed parts are also influenced by the cooling fan used during the printing process. Research has shown that there is an inverse relationship between the cooling air flow rate and both the dimensional accuracy and mechanical strength of the printed components. A higher cooling airflow rate improves dimensional quality by stabilizing the printed layers; however, it may reduce the mechanical strength of the printed parts [6]. Therefore, optimizing the cooling conditions is essential to achieve a balance between dimensional accuracy and mechanical performance.

Infill density

ID has a significant influence on the tensile strength of 3D printed PLA specimens. Independence of the selected infill pattern, an increase in ID has been shown to considerably improve the tensile strength of PLA parts produced using FDM technology. Higher infill densities increase the internal material volume of the structure, resulting in improved load-bearing capacity and enhanced mechanical performance of the printed components.

Infill pattern

In addition to ID, FDM G-code parameters also include the option to select different infill patterns. Various infill pattern types exist, and their selection can significantly influence the mechanical properties of printed components. In the study titled "Investigation of the Effect of Infill Pattern and Layer Thickness on the Mechanical Strength of PLA Material in 3D Printing Technology," several commonly used infill patterns were analyzed [7]. Among the evaluated patterns, the triangular infill pattern provided the highest mechanical strength, whereas the zigzag pattern exhibited the lowest mechanical performance. The grid infill pattern forms a lattice structure consisting of intersecting perpendicular lines that create a mesh-like pattern within the printing area. This pattern provides moderate strength while using a relatively small amount of material. Due to this balance between material usage and structural strength, the grid pattern is commonly preferred for functional prototypes and objects subjected to light mechanical loads, and it is also suitable for faster 3D printing applications.

Within the scope of this study, certain G-code-related printing parameters were intentionally kept constant to establish a controlled experimental environment and to ensure a reliable evaluation of the selected variables. These fixed parameters include layer height, nozzle diameter, infill pattern, and cooling conditions as detailed in the following section.

MATERIALS AND METHODS

Experimental Procedure

PLA filament supplied by KIMYA was used in all experiments. Considering the hygroscopic nature of PLA, the material was stored under controlled conditions prior to printing in order to minimize moisture absorption and ensure process stability. All specimens were manufactured using a closed-chamber FDM system BCN3D Epsilon W27 under controlled environmental conditions of approximately 24°C ambient temperature and 40% relative humidity. These conditions were maintained throughout the experiments to reduce moisture-related variability and improve reproducibility.

In addition, to establish a controlled experimental framework, several process parameters were kept constant. The build plate temperature was maintained at 50 °C and the printing temperature was fixed at 200 °C for all experimental runs to ensure consistency. A triangular infill pattern, which has been reported to provide high mechanical strength, was used in all prints. The layer height was set to 0.2 mm, and a 0.4 mm brass nozzle was employed throughout the experiments. The cooling fan speed was fixed at 80% to achieve a balance between sufficient material solidification and stable interlayer bonding. Excessive cooling may weaken interlayer adhesion, whereas insufficient cooling can lead to dimensional inaccuracies; therefore, an intermediate value was selected to ensure consistent printing conditions.

Furthermore, the build orientation was carefully selected to minimize the need for support structures while ensuring that the clip mounting surface remained on the upper side. This configuration was preferred to reduce surface-induced dimensional deviations and maintain assembly tolerances during clip installation. By controlling these parameters, the influence of external factors was minimized, allowing a focused evaluation of the primary process variables, namely WLC, ID, and PS.

The experimental procedure developed within the scope of this study consists of six main stages, designed to systematically determine the optimal process parameters affecting the mechanical properties, filament consumption, and production time of PLA specimens produced via the FDM process.

I. A comprehensive literature review was conducted to identify the key process parameters affecting FDM printing performance. Based on this review, the input parameters and their corresponding levels were determined.
II. A tensile test specimen was designed in SolidWorks according to the ASTM D638 Type I standard. The designed model was then converted into STL format, which is required for the slicing process.
III. Based on the parameter combinations determined using the Taguchi experimental design method, G-code files were generated using the Stratos slicing software.
IV. The generated G-code files were printed using a BCN3D Epsilon W27 3D printer. During the printing process,

output parameters such as filament consumption (m) and printing time (minutes) were recorded.

V. A total of 27 specimens, consisting of three repetitions for each experimental condition, were subjected to tensile testing using a UVE (MNR050) Universal Testing Machine at a crosshead speed of 5mm/min.

VI. The experimental results obtained were analyzed using the Taguchi method, and ANOVA was performed to evaluate the significance of the process parameters.

Accordingly, the input process parameters considered in this study WLC, ID, and PS which are summarized in Table 1. In line with the Taguchi experimental design, each parameter was evaluated at three different levels WLC (2, 4, and 6), ID (20%, 50%, and 90%), and PS (40, 80, 120 mm/s) to determine the optimal combination for improved performance.

There is various testing methods used to evaluate the properties of different types of plastics. Among these, ASTM D638 is one of the most widely used standards for determining the tensile properties of plastic materials. This test is performed by applying a tensile force to a specimen and analyzing various characteristics of the material under stress. The ASTM D638 standard consists of five different specimen specifications. Within the scope of this study, the ASTM D638 Type I tensile test specimen which is shown in Figure 1 was selected because it allows for a more effective analysis of the influence of ID, which was chosen as one of the input parameters in the experimental design.

A tensile test is a fundamental materials science test in which a specimen is subjected to uniaxial tensile forces until fracture occurs. The results obtained from this test are commonly used for material selection in engineering applications, quality control, and predicting how materials will behave under different loading conditions. Tensile strength is defined as the maximum tensile stress that a material can withstand before failure or fracture. This stress corresponds to the highest stress value observed in the stress–strain diagram and is calculated using the following Equation (1):

$$\sigma_t = \frac{F_{max}}{A_0}$$

where F_{max} represents the maximum applied force and A_0 denotes the initial cross-sectional area of the specimen.

According to the Taguchi L9 experimental design, tensile tests were conducted on a total of 27 specimens, grouped into sets of three for each parameter combination. The tests were performed using a UVE MNR050 universal testing machine with a capacity of 50 kN, at a constant crosshead speed of 5 mm/min. The experimental setup and testing configuration are illustrated in Figure 2, while the fractured specimens obtained after testing are presented in Figure 3.

Experimental Results

The experimental results, including mechanical strength, filament consumption, and production time, were systematically recorded and prepared for further analysis.

Table 1. Process input factors algorithms

Items	Specimen quantity	Input parameters		
		Wall line count	Infill density (%)	Print speed (mm/s)
A1	3	2	20%	40
A2		2	20%	40
A3		2	20%	40
B1	3	2	50%	80
B2		2	50%	80
B3		2	50%	80
C1	3	2	90%	120
C2		2	90%	120
C3		2	90%	120
D1	3	4	20%	80
D2		4	20%	80
D3		4	20%	80
E1	3	4	50%	120
E2		4	50%	120
E3		4	50%	120
F1	3	4	90%	40
F2		4	90%	40
F3		4	90%	40
G1	3	6	20%	120
G2		6	20%	120
G3		6	20%	120
H1	3	6	50%	40
H2		6	50%	40
H3		6	50%	40
I1	3	6	90%	80
I2		6	90%	80
I3		6	90%	80

The tensile test results provide detailed insight into the mechanical performance of the specimens. As presented in Table 2, key parameters such as maximum force (N), strain (%), tensile strength (MPa), and elastic modulus (MPa) were obtained. These mechanical properties enable a comprehensive evaluation of the structural behavior of the printed specimens under tensile loading.

In addition to the mechanical properties, process related outputs, including filament consumption and print-

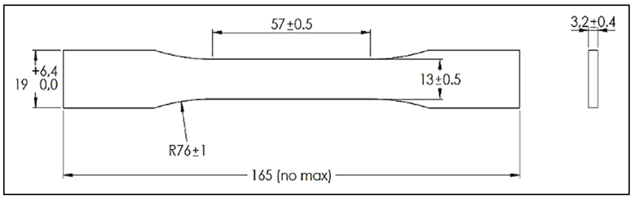

Figure 1. ASTM D638 type 1 - tensile test specimen.

Figure 2. UVE MNR050 tensile test machine.

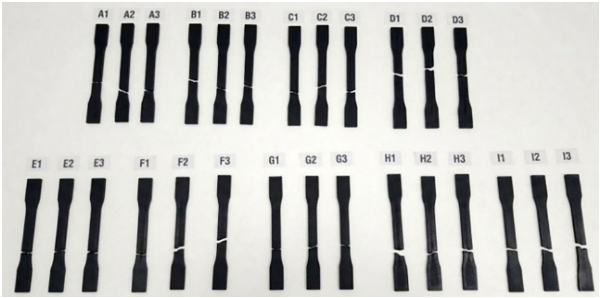

Figure 3. Tensile test specimens.

Table 2. Tensile test findings

Specimen	Fmax (N)	E (MPa)	σt (MPa)	ε (%)
A1	1844.641	2627.867	42.069	4.526
A2	1858.904	2612.023	41.753	2.563
A3	1901.203	2651.828	42.704	2.135
B1	2011.918	2998.894	43.948	2.828
B2	1831.357	2837.927	39.715	1.660
B3	2031.600	2905.050	44.025	2.342
C1	2301.954	3595.173	48.554	1.708
C2	2325.173	3581.178	49.018	3.174
C3	2311.136	3540.039	48.477	1.779
D1	2062.948	2924.634	44.978	1.900
D2	2134.676	3048.559	47.793	2.023
D3	2199.706	3000.864	49.685	3.377
E1	2164.256	3069.198	47.258	3.637
E2	2102.350	3133.051	46.481	2.967
E3	2176.825	3127.246	47.981	3.348
F1	2733.224	3981.620	59.161	2.676
F2	2826.929	3983.078	61.858	4.089
F3	2670.678	3968.812	58.228	1.712
G1	2235.871	3124.262	48.152	1.853
G2	2309.029	3165.595	49.550	2.325
G3	2352.569	3162.160	50.716	2.363
H1	2824.032	3884.153	64.057	2.726
H2	2847.627	4143.654	65.323	2.104
H3	2779.362	3919.540	63.233	5.392
I1	3082.907	4269.855	67.368	2.210
I2	3125.733	4343.747	68.386	2.357
I3	3152.791	4466.904	69.105	2.961

ing time, were also measured. The complete set of output data, combining both mechanical and production-related parameters, is summarized in Table 3. This data set forms the basis for subsequent statistical analysis, including S/N ratio evaluation and ANOVA, as well as optimization using the Taguchi method.

Based on experimental tests, and subsequent analyses, the obtained data were systematically compiled. These output parameters were further analyzed using signal-to-noise (S/N) ratios and ANOVA to identify the most influential factors.

KEY FINDINGS

In experimental results, Taguchi introduced a performance evaluation criterion known as the signal-to-noise (S/N) ratio, which is used as an analysis variable to assess the robustness and quality of experimental results.

Several assumptions are considered in the calculation of the S/N ratio, including "smaller is better," "nominal is best," and "larger is better." Regardless of the selected assumption, the primary objective in all cases is to maximize the S/N ratio in order to achieve optimal performance and minimize variability.

The findings obtained from the output parameters were evaluated in terms of mechanical strength, filament consumption, and printing time. The experimental results were analyzed based on the appropriate S/N ratio criteria corresponding to each output parameter. According to the ANOVA results, WLC was identified as the most statistically significant factor affecting tensile strength, with the highest contribution ratio. In contrast, ID and PS showed greater influence on production time and material consumption. The statistical analysis confirms that WLC plays a dominant role in mechanical performance, while ID and PS are more critical in terms of manufacturing efficiency.

Analysis of Strength, Material Consumption and Time

Strength

In this study, higher strength values were considered as an indicator of better-quality performance. Accordingly, the system was optimized based on the "larger is better" assumption in the Taguchi analysis. According to these findings, the highest S/N ratios were obtained at the following factor levels:

- For the WLC factor, the highest effect was observed as 6 with a contribution ratio of 56.21%.

Table 3. Process output findings

Item	Specimen quantity	Output parameters			
		Tensile strength (Mpa)	Average of tensile strength (mpa)	Filament consumption (meters)	Time (min)
A1	3	42.069	42.175	0.776	28
A2		41.753		0.776	28
A3		42.704		0.776	28
B1	3	43.948	42.563	0.993	21.33
B2		39.715		0.993	21.33
B3		44.025		0.993	21.33
C1	3	48.554	48.683	1.276	22.33
C2		49.018		1.276	22.33
C3		48.477		1.276	22.33
D1	3	44.978	47.485	0.836	17.33
D2		47.793		0.836	17.33
D3		49.685		0.836	17.33
E1	3	47.258	47.240	1.03	17.66
E2		46.481		1.03	17.66
E3		47.981		1.03	17.66
F1	3	59.161	59.749	1.28	48
F2		61.858		1.28	48
F3		58.228		1.28	48
G1	3	48.152	49.473	0.893	14.667
G2		49.55		0.893	14.667
G3		50.716		0.893	14.667
H1	3	64.057	64.204	1.067	40
H2		65.323		1.067	40
H3		63.233		1.067	40
I1	3	67.368	68.286	1.286	28
I2		68.386		1.286	28
I3		69.105		1.286	28

Table 4. Anova results for strength

Source	Means of S/N ratios Levels			DF	Seq SS	Adj MS	Fac eff (%)	F	p
	1	2	3						
WLC	32.94	34.18	35.58	2	10.40	5.20	56.21	30.27	0.03
ID	33.31	34.07	35.32	2	6.20	3.10	33.49	18.04	0.05
PS	34.73	34.27	33.71	2	1.56	0.78	8.45	4.55	0.18
Res. Err.				2	0.34	0.17	1.86		
Total				8	18.51		100		

DF: Degrees of freedom; Seq SS: Sum square; Adj MS: Adjusted mean square; Fac. eff: Factor effect; Res. Err.: Residual error.

- For the ID factor, the highest effect was observed as 90% with a contribution ratio of 33.49%.
- For the PS factor, the highest effect was observed as 40 mm/s with a contribution ratio of 8.45%.

These results indicate that the WLC parameter has the most significant influence on the tensile strength, followed by ID and PS according to Anova results in Table 4.

Table 5. Anova results for filament consumption

Source	Means of S/N ratios Levels			DF	Seq SS	Adj MS	Fac eff (%)	F	p
	1	2	3						
WLC	0.05	-0.28	-0.59	2	0.61	0.30	2.80	3.59	0.22
ID	1.58	-0.25	-2.15	2	20.86	10.43	95.68	122.96	0.01
PS	-0.17	-0.19	-0.46	2	0.16	0.0	0.75	0.96	0.51
Res. Err.				2	0.17	0.08	0.78		
Total				8	21.80		100		

DF: Degrees of freedom; Seq SS: Sum square; Adj MS: Adjusted mean square; Fac. eff: Factor effect; Res. Err.: Residual error.

Table 6. Anova results for printing time

Source	Means of S/N ratios Levels			DF	Seq SS	Adj MS	Fac eff (%)	F
	1	2	3					
WLC	-27.50	-27.78	-28.10	2	0.55	0.27	0.58	3.27
ID	-25.68	-27.85	-29.85	2	26.05	13.02	27.71	155.56
PS	-31.54	-26.77	-25.08	2	67.25	33.62	71.53	401.60
Res. Err.				2	0.17	0.08	0.18	
Total				8	94.01		100	

DF: Degrees of freedom; Seq SS: Sum square; Adj MS: Adjusted mean square; Fac. eff: Factor effect; Res. Err.: Residual error.

Material Consumption

Minimizing filament consumption was considered an important performance criterion. Therefore, the system was optimized based on the "smaller is better" assumption in the Taguchi analysis. According to these findings, the highest S/N ratios were obtained at the following factor levels shown in Table 5:

- For the WLC factor, the highest effect was observed as 2 with a contribution ratio of 2.80%.
- For the ID factor, the highest effect was observed as 20% with a contribution ratio of 95.68%.
- For the PS factor, the highest effect was observed as 40 mm/s with a contribution ratio of 0.75%.

These results indicate that the ID parameter has the most significant influence on filament consumption, while the effects of WLC and PS are relatively limited.

Printing Time

Minimizing the printing time was considered an important objective to improve production efficiency. Therefore, the system was optimized based on the "smaller is better" assumption in the Taguchi analysis. The ANOVA results obtained using the time variable are presented in the corresponding table. According to these findings, the highest S/N ratios were obtained at the following factor levels:

- For the WLC factor, the highest effect was observed as 2 with a contribution ratio of 0.58%.
- For the ID factor, the highest effect was observed as 20% with a contribution ratio of 27.71%.
- For the PS factor, the highest effect was observed as 120 with a contribution ratio of 71.53%.

These results indicate that the PS parameter has the most significant influence on printing time, followed by ID, while the effect of WLC is relatively limited illustrated in S/N ratios shown in Table 6 below.

RESULTS AND DISCUSSION

The Taguchi-based optimization results indicate that WLC is the most influential parameter governing tensile strength, whereas ID, and PS predominantly affect production time and material consumption. This can be attributed to the fact that WLC directly determines the number of outer perimeters, thereby enhancing load-bearing capacity and interlayer bonding strength. In contrast, ID and PS mainly influence the internal structure and deposition rate, which are more closely associated with manufacturing efficiency rather than structural reinforcement.

Beyond their individual contributions, a notable synergistic interaction between ID and PS was identified. At elevated PS values, the reduced residence time of extruded material limits interlayer diffusion, leading to inadequate bonding and the formation of internal voids. This effect becomes more critical at lower ID levels, where the reduced material density amplifies structural discontinuities. Conversely, higher ID values can partially mitigate the adverse effects of increased PS by improving internal support and reducing porosity. These findings highlight that the combined influence of PS and ID plays a decisive role in balancing mechanical performance and internal integrity.

The observed reduction in tensile performance at higher PS values can be further explained by increased porosity formation. As the printing speed increases, insufficient bonding between adjacent filaments leads to micro-voids, which act as stress concentration sites and initiate premature failure under tensile loading. This behavior is consistent with the fundamental characteristics of FDM processes, where interlayer adhesion is strongly dependent on thermal diffusion and bonding time.

Although tensile testing was conducted using standard specimens, the selected geometry and loading conditions were designed to represent the critical mechanical behavior of CCFs. In real applications, CCF components are exposed to localized stresses and repetitive mechanical interactions, where both strength and structural integrity are essential. Therefore, the obtained results provide a representative and practically relevant basis for evaluating the performance of CCFs under operational conditions.

The interpretation of these findings should be considered within the constraints of the experimental setup. All experiments were conducted using a single material type PLA brand name is called KIMYA, which may limit the generalizability of the results to other thermoplastics with different thermal and rheological properties. Furthermore, the experiments were carried out on a closed-chamber FDM system on BCN3D Epsilon W27 3D Printer machine and under controlled environmental conditions approximately 24°C ambient temperature and 40% relative humidity. Such conditions can significantly influence cooling behavior, interlayer adhesion, and dimensional stability, and may lead to different outcomes in open-frame systems or varying environmental conditions for reporoducibility.

In addition, several process parameters were kept constant, including a layer height of 0.2 mm, a brass nozzle diameter of 0.4 mm, and a cooling fan speed of 80%. While this controlled approach enables a focused investigation of WLC, ID, and PS, it restricts the assessment of potential interactions between these fixed parameters and the studied variables. Variations in layer height or cooling conditions, for instance, could alter interlayer bonding mechanisms and consequently affect mechanical performance.

Despite these limitations, this study makes a significant application-oriented contribution by focusing on functional CCF components rather than solely on conventional standardized test specimens. Although the experiments were conducted using standard tensile specimens, the findings are interpreted in the context of real fixture applications. By integrating mechanical strength, production time, and filament consumption into a unified optimization framework, the study provides a comprehensive basis for decision-making in in-house fixture production. Future work should extend this approach by incorporating different materials, printer configurations, and environmental conditions, as well as advanced multi-objective optimization techniques.

CONCLUSION

This study aims to investigate the effects of process parameters on the strength, filament consumption, and printing time of PLA materials used in the production of fixtures. Within this scope, WLC, ID, and PS were considered as primary process parameters. The experiments were carried out according to the Taguchi L9 experimental design, using a total of 27 specimens, where each factor was evaluated at three different levels.

Based on the calculated signal-to-noise (S/N) ratios, the highest strength value was obtained with the factor level combination of WLC 6, ID 90, and PS 40. For filament consumption, the effect of ID was calculated as 95.68%, while the contribution of WLC was 2.80%, and the optimal combination was determined as WLC 2, ID 20, and PS 40. For the printing time, the results indicated that the most influential factors were PS 71.53% and ID 27.71%, with the optimal parameter combination identified as WLC 2, ID 20, and PS 120.

These findings demonstrate how process parameters influence AM processes using PLA to enhance production efficiency and mechanical performance. Identifying critical factors affecting strength, material consumption, and production time provides valuable insights for improving manufacturing efficiency and product quality.

This study identifies WLC as a key parameter controlling the mechanical performance of CCF components and improving process efficiency. Future studies may focus on different materials, more complex geometries, and tighter tolerances to further advance this field.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Serhat Mustafa: Conceptualization, Data curation, Investigation, Methodology, Resources, Software, Valid- ation, Visualization, Literature Review, Draft Preparation

Dilek Murat: Data Curation, Formal Analysis, Methodology, Software, Visualization, Draft Preparation

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Statement on the Use of Artificial Intelligence

Artificial intelligence was not used in the preparation of experiments and article states.

Ethics

There are no ethical issues with the publication of this manuscript.

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