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OPTIMISING 3D PRINT PARAMETERS FOR L-JOINT STRENGTH USING TAGUCHI METHOD

Aleyna TAŞKIN[1], Cengiz Görkem DENGİZ[2*]

[1]*Ondokuz Mayıs University, Faculty of Engineering, Department of Mechanical Engieering, 55139, Samsun, Türkiye*
[2] *Ondokuz Mayıs University, Faculty of Engineering, Department of Mechanical Engieering, 55139, Samsun, Türkiye*

Abstract: Additive manufacturing offers advantages such as reduced waste and cost-effectiveness, and its use is increasing in industries such as aerospace and automotive. One of the additive manufacturing methods, fused deposition modelling (FDM), has a wide range of applications. This study investigated the effects of printing parameters on the strength of L-joints made using FDM. Polylactic acid (PLA), a biodegradable and recyclable material, was used to produce L-joints. The study analyses the effects of three printing parameters: nozzle temperature, filling ratio, and printing pattern. Taguchi method was used to optimise these parameters, and then ANOVA (analysis of variance) was performed to determine their contributions to the joint strength. Optimum values were obtained at 210°C nozzle temperature, 70% filling rate and zigzag pattern. The results show that the printing pattern and filling ratio significantly affect the strength of the joint, while nozzle temperature has less effect. The zigzag printing pattern and higher filling rate (70%) provided the strongest joints, reaching a maximum force of 358.4 N during tensile tests. The study concluded that optimising 3D printing parameters is very important to increase the strength and quality of printed joints.

Keywords: Additive manufacturing, Fused deposition modelling, Polylactic acid, Printing parameters, L-joint strength, Taguchi method

***Corresponding author:** Ondokuz Mayıs University, Faculty of Engineering, Department of Mechanical Engieering, 55139, Samsun, Türkiye
E mail: gorkem.dengiz@omu.edu.tr (C. G. DENGİZ)
Aleyna TAŞKIN https://orcid.org/ 0000-0002-8308-9957
Cengiz Görkem DENGİZ https://orcid.org/ 0000-0003-1308-3223

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1. Introduction

The application of additive manufacturing (AM) in producing parts with complex geometries is expanding rapidly. This advanced production technique fabricates components by depositing material layer by layer, offering significant advantages over traditional manufacturing methods (Cai et al., 2024). These advantages include lower production costs, reduced material waste, elimination of secondary processes, and accelerated production times. Moreover, AM is particularly advantageous for prototyping, small-scale production, and manufacturing specialised parts (Tharanikumar et al., 2024). Fused deposition modelling (FDM) is frequently utilised among the various AM techniques due to its ease of use and ability to produce aesthetically refined products. Recently, FDM has garnered attention for its environmental benefits, including biodegradability and recyclability (Sultana et al., 2024). This method is widely employed across aerospace, dental implants, and automotive manufacturing industries. In FDM, parts are fabricated by heating filament material and depositing it layer by layer in predefined patterns dictated by the nozzle path (Vinay et al., 2024). Commonly used materials for FDM include polylactic acid (PLA), thermoplastic polyurethane (TPU), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PETG), nylon, and polyether ether ketone (PEEK) (Goh et al., 2024). PLA is highly popular among these due to its recyclability, renewability, and biocompatibility. PLA, a thermoplastic polyester derived from renewable resources like corn starch or sugarcane, is environmentally friendly and suitable for manufacturing joints, prototypes, and educational tools (Ogaili et al., 2024). Joints are structural components designed to connect at least two parts, ensuring effective load transfer, support, and stability. For example, in aerospace applications, joints are critical for assembling wing sections to the fuselage, where they must withstand complex load conditions, including torsion and vibration. L-joints, a specific type of joint, are formed by combining two or more elements at a 90-degree angle. These joints play a critical role in various structural applications, including composite structures, steel plate walls, and flange joints in wind turbines (Li et al., 2019). Due to their angular geometry, L-joints are susceptible to damage under loading conditions such as tension, compression, bending, and dynamic impacts (Rucka, 2010). Understanding the mechanical behaviour and strength of L-joints is essential for accurate damage detection, failure analysis, and improving the reliability of engineering applications (Seo & Varma, 2017). Several factors influence L-joint strength, including material properties, joint geometry, loading conditions, and production methods. In FDM-produced joints, printing parameters such as nozzle temperature, fill density, and print pattern significantly affect joint strength. The quality and performance of 3D-printed parts depend heavily on optimising printing parameters. The Taguchi method, a statistical optimisation approach, is widely used to refine these parameters. By employing orthogonal array designs, the Taguchi method systematically evaluates the effects of multiple parameters on the desired output, minimizing variability and reducing the number of required experiments. This efficient methodology enhances part quality by identifying the optimal combination of printing parameters (Kim et al., 2019). Extensive research has examined the influence of printing parameters on the mechanical properties of 3D-printed parts, highlighting notable trends and conclusions. For instance, nozzle temperature and fill density variations have consistently shown a direct impact on tensile strength, with higher fill densities generally improving part durability. Studies have also underscored the significance of print patterns, where specific arrangements like cross (+45°/−45°) designs facilitate more uniform load distribution, thereby enhancing strength. Collectively, these findings emphasise the pivotal role of parameter optimisation in tailoring mechanical properties to specific application requirements. For example, Gozluklu and Coker investigated the dynamic delamination behaviour of L-shaped composite materials commonly used in civil aviation. Their study revealed that kinetic energy constitutes a significant portion of total energy during crack propagation, even under quasi-static loading. Furthermore, they observed the nucleation and propagation of secondary cracks due to variations in thickness (Gozluklu & Coker, 2012). Yavas et al. studied delamination in the curved region of bonded L-shaped plates, emphasising the critical role of pre-crack size on delamination toughness (Yavas et al., 2012). Arca reinforced L-shaped composite laminates with carbon nanotube-reinforced and thin-layered carbon fibre fabric to mitigate delamination issues in aviation and wind turbine applications. Their findings highlighted the superior performance of fabric reinforcements over carbon nanotubes in preventing delamination without increasing part weight or altering material properties (Arca, 2014). Johansson explored the effects of material properties, print density, extruder temperature, print speed, and layer height on the tensile strength of 3D-printed specimens. Using PLA, ABS, and PET materials, the study found that PLA exhibited the highest strength, while ABS showed the lowest. Strength increased with higher print density and extruder temperature but decreased with higher print speed and layer height. Moreover, enclosed designs provided better layer adhesion compared to open designs (Johansson, 2016). Similarly, Günay et al. analysed the impact of printing speed, fill density, and print angle on mechanical properties. Using the Taguchi method, they identified fill density as the most influential parameter on tensile strength, followed by print angle and speed (Günay et al., 2020). Zubrzycki et al. investigated the effects of fill density and print patterns (line, grid, and honeycomb) on tensile strength in PLA, PETG, and ABS samples. They observed that higher fill densities generally enhanced strength, with optimal strength achieved using specific patterns for each material (Zubrzycki et al., 2022). Bayraktar et al. examined the influence of melting temperature, layer thickness, and print patterns (+45°/−45°, horizontal and vertical) on PLA samples. Their findings indicated that tensile strength decreased with lower layer thickness and melting temperature, while the cross (+45°/−45°) pattern outperformed others due to more uniform load distribution and reduced stress concentration (Bayraktar et al., 2017). While numerous studies have focused on the effects of printing parameters on the tensile strength of 3D-printed parts, research on L-joints subjected to mixed loading conditions is limited. This study addresses this gap by investigating the influence of nozzle temperature, fill density, and print pattern on the strength of L-joints. The Taguchi method was employed for experimental design, and analysis of variance (ANOVA) was used to identify optimal printing parameters. The findings of this research contribute to a deeper understanding of the mechanical behaviour of L-joints, providing insights for an improved design and enhanced structural reliability.

2. Materials and Methods

2.1. Material

In the study, PLA filament was preferred in producing L-joints due to its recyclability and ease of application. Filameon brand PLA filament with a diameter of 1.75 mm was used in the production of L-joint elements with the Creality brand CR-10 S5 model 3D printer. PLA filament properties are given in Table 1. The dimensions of the produced L-joint elements are given in Figure 1.

Table 1. PLA filament properties

Nozzle Temperature (°C)	Diameter (mm)	Density (g/cm³)	Tensile Strength (MPa)	Extension Strain (%)
190-230	1.75	1.24	53	6

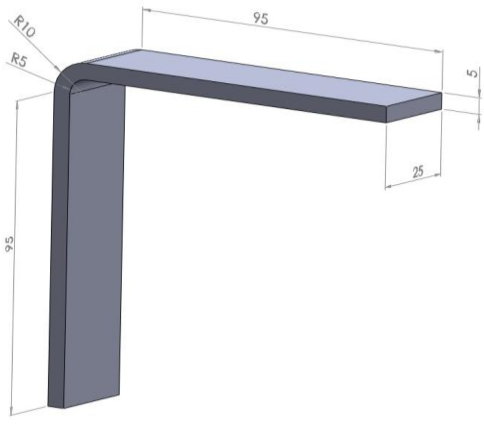

Figure 1. L-joint sample dimensions.

2.2. Methods

The study produced L-joint samples using the Creality brand CR-10 S5 model 3D printer and the G code Ultimaker Cura program. The table temperature is set to 60°C, the recommended table temperature for PLA material. To prevent the sample from separating from the table surface during printing, masking tape was placed on the table, and the printing speed was applied as 50 mm/s. G code was created by selecting the nozzle temperature, filling ratio, and print pattern, which were determined using Taguchi's experimental design. Then, the generated G code was transferred to the printer and the L-joint samples shown in Figure 2 were produced.

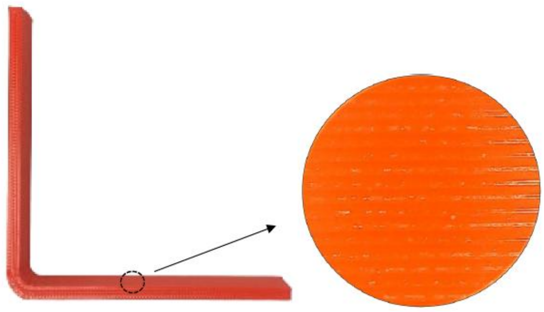

Figure 2. The l-joint sample produced with a 3D printer.

To determine the strength of the produced samples, tensile tests were performed using an INSTRON brand universal testing machine with a load capacity of 100 kN. However, due to its geometry, the L-joint element was unsuitable for the tensile device. Therefore, the necessary measurements were taken from the device, and the eared jaw, bottom plate, and pin, as shown in Figure 3, were designed.

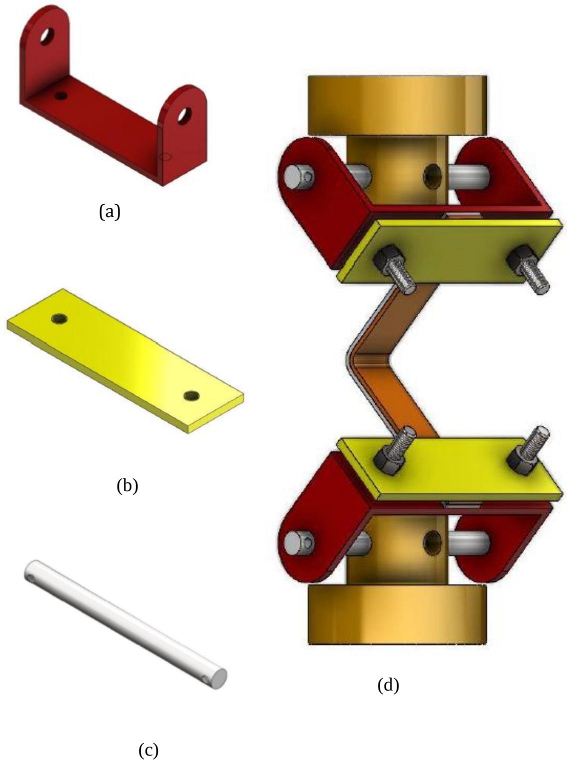

Figure 3. The jaw (a), bottom plate (b), pin (c) and assembly drawing (d).

After the design was completed, the 5 mm thick sheet metal was cut with a laser and the bending process was carried out on the press brake machine. Then, these produced parts were connected to the tensile testing device. Tensile L-joint tests were carried out at a tensile speed of 1.3 mm/min (Figure 4).

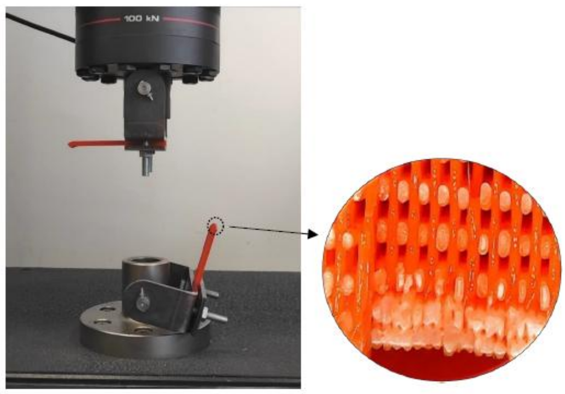

Figure 4. The tensile test applied to L-joint element.

Afterwards, the maximum forces at which the samples broke were determined with the data obtained from the tensile test. According to these maximum forces, Taguchi analysis was performed, and the optimum printing parameters were determined. ANOVA analysis detected the contribution (effect) rates of the parameters on the maximum force. In addition, regression analysis was performed to obtain the maximum force equality.

2.3. Experimental Design

This study used the Taguchi experimental design method to determine the optimum printing parameters in sample production with a 3D printer. Taguchi's experimental design is used to optimise production processes and improve product quality. It also saves time and cost by minimizing the number of experiments. The Taguchi method examines the relationship between multiple variables with the minimum number of experiments (Setyo Pradana & Sulistiyowati, 2022). Thus, optimum variables will be obtained to ensure quality production. This enables the Taguchi method to be used in many production areas, especially engineering (Mitra, 2011). Nozzle temperature, filling ratio and printing pattern were selected in this study as variable design factors (Table 2). Nozzle temperature was 190, 200 and 210°C, filling ratio was 50, 60 and 70%. The printing pattern was determined as grid, line and zigzag (Figure 5). Taguchi analysis was performed to determine the optimum values of these factors.

Table 2. Variable design factors

Factors	Lower	Middle	Upper
Nozzle Temperature (°C)	190	200	210
Filling Ratio (%)	50	60	70
Print Pattern	Grid	Line	Zigzag

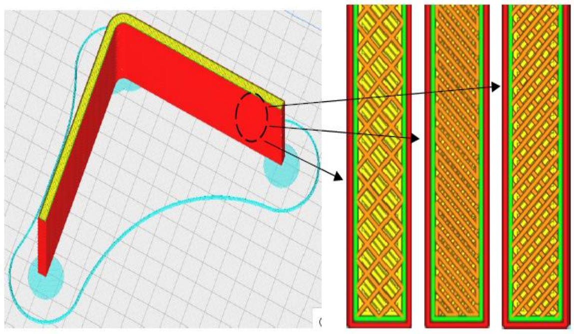

Figure 5. Grid (a), zigzag (b) and line (c) pattern.

Table 3. L9 orthogonal array

Experiment No	Factors			Output Parameters
	Nozzle Temperature (°C)	Filling Ratio (%)	Print Pattern	Max. Force (N)
1	190	50	Zigzag	261.225
2	190	60	Line	262.072
3	190	70	Grid	263.748
4	200	50	Grid	173.522
5	200	60	Zigzag	251.270
6	200	70	Line	301.397
7	210	50	Line	228.603
8	210	60	Grid	231.620
9	210	70	Zigzag	358.363

The maximum forces of L-joint samples during the tensile test were selected as the output parameter. The effect of variable design factors (nozzle temperature, filling ratio and printing pattern) on the maximum force was investigated. 9 experimental designs were obtained by selecting the 3-factor 3-level L9 (3^3) orthogonal array in the Minitab software. According to this experimental design, L-joint samples were produced with a 3D printer and tensile tests were performed. The maximum force values obtained from the tests were entered into the Minitab software as the output parameter (Table 3) In the Taguchi method, signal-to-noise (S/N) ratios are used to reduce the variability of the process and analyse the performance of the system. While the signal (S) represents successful and desired results, noise (N) represents unwanted variability, such as differences and errors. The S/N ratio optimises the process by determining signal and noise differences. The higher this ratio is, the more accurate and high-quality the process is. The S/N ratio is divided into three groups "largest is best", "smallest is best", and "nominal is best", according to the desired output parameter (Negrete, 2020). Since the highest value of the maximum force (output parameter) is desired in this study, the "largest is best" S/N ratio in equation 1 was preferred. In the equation, Y represents the quality variable, and n represents the number of experiments (Hikmat et al., 2021).

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right] \tag{1}$$

After Taguchi analysis, ANOVA was applied to determine the effect (contribution) ratio of nozzle temperature, filling ratio and printing parameter on the maximum force. ANOVA determines the statistical differences in the means between two or more groups. Thus, it presents the effect of design factors on the output parameter by determining whether these differences are significant or insignificant (Driscoll et al., 2024). After ANOVA, regression analysis was performed to determine the relationship between design differences and output parameters. As a result of regression analysis obtained the equation gives the output parameter (maximum force) value without performing experimental application.

3. Results and Discussion

The mean effect graph of S/N ratios representing the effect of printing parameters on maximum force is given in Figure 6. Upon reviewing the figure, it can be observed that as the nozzle temperature increases, the maximum force initially decreases and then increases. This rise in nozzle temperature improves the adhesion quality between the layers, making the material more durable (Johansson, 2016; Bayraktar et al., 2017). It was also found that the maximum force increases as the fill ratio rises. This suggests that a higher fill ratio has a positive impact on the maximum force (Johansson, 2016; Günay et al., 2020; Zubrzycki et al., 2022). As the fill ratio increases, the amount of material in the part increases, closing the gaps and enhancing the material's resistance to applied loads. When examining the effect of printing patterns on the maximum force, it was determined that the highest maximum force occurred in zigzag, followed by line and then grid patterns, in descending order. This indicates that the printing pattern significantly affects the strength of the part. The appropriate printing pattern should be selected based on the part's load conditions. In this study, L-joint elements were subjected to mixed load, and the zigzag pattern provided the best resistance. From the figure, the optimal values for achieving maximum force were 210°C for nozzle temperature, 70% for infill ratio, and the zigzag printing pattern.

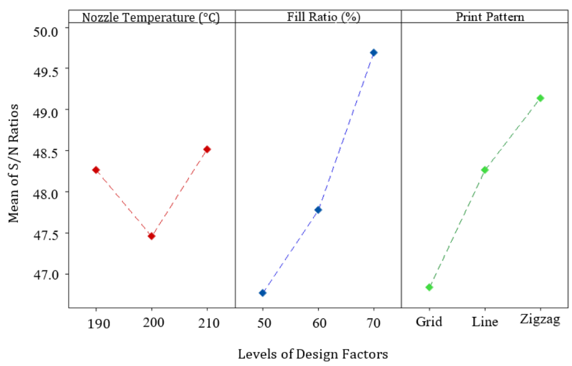

Figure 6. The mean of S/N ratios for maximum force.

Figure 7 shows the force-displacement values of 9 experimental samples determined by the Taguchi method. When the figure is examined, the lowest maximum force (173.5 N) was determined in the 4th experiment. The 4th experimental sample was produced at 200°C nozzle temperature, 50% filling ratio and grid printing pattern. The 200°C nozzle temperature negatively affected the adhesion of the filaments to each other. At low temperatures, the filaments adhered weakly to each other and increased the formation of gaps within the part. This situation also reduced the resistance of the part against the tensile force. The 50% filling ratio created the part with less material and caused more gaps. The grid pattern could not distribute the load on the part homogeneously. Therefore, the lowest force was determined in the 4th experimental sample. The highest maximum force (358.4 N) was obtained in the 9th experiment produced at 210°C nozzle temperature, 70% filling ratio and zigzag printing pattern. With the increase in temperature, the adhesion of the filaments improved, and a stronger bond was formed between the layers. When the filling ratio is 70%, the part consists of more material. Thus, the formation of gaps inside the part is reduced. This increases the resistance of the material against tensile force. The zigzag pattern prevents stress concentrations by distributing the load on the part more homogeneously than other patterns and increases durability.

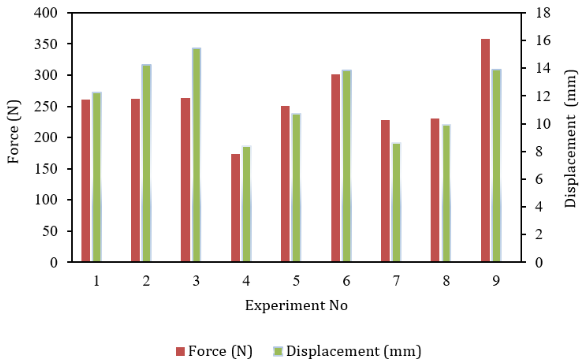

Figure 7. Force-displacement values of L-joint samples.

Figure 8 shows the force-elongation graph of the 4th and 9th test samples. When the graph is examined, it is observed that the 9th sample exhibits approximately two times more elongation compared to the 4th sample. In the 9th sample, the high nozzle temperature, high filling ratio and appropriate printing pattern delayed the rupture by allowing the material to carry more force in the plastic region. Therefore, the strength of the 9th sample was obtained higher. In the 4th sample, the material ruptures rapidly after exceeding the elastic limit. The plastic deformation zone is shorter compared to the 9th sample. The sample reaches the maximum force earlier and ruptures. This shows that the part's resistance against the applied force is lower.

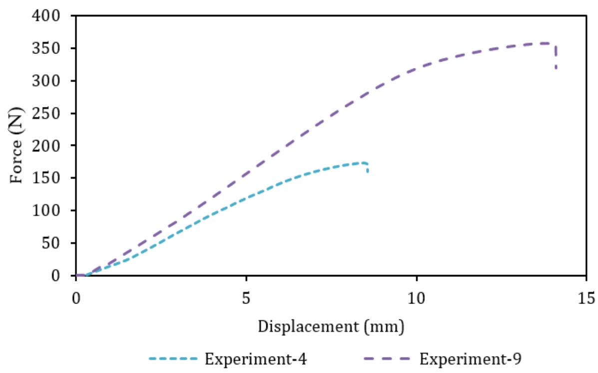

Figure 8. Force-displacement graph of 4th and 9th samples.

The ANOVA results, which were conducted to determine the contribution rates of the printing parameters on the maximum force, are given in Table 4. According to the table, the most effective parameter of the maximum force is the filling ratio, with a rate of 57.95%. This value indicates that the filling ratio significantly affects the part's strength. The most effective parameter after the filling ratio is the printing pattern, with a rate of 32.88%. The least effective parameter is the nozzle temperature, with a rate of 6.87%. In addition, when the P value in ANOVA is greater than 0.05, the effect of that factor on the output parameter is considered insignificant (Rajabi et al., 2015). When the table is examined, it is seen that the P value of the nozzle temperature and the printing pattern is greater than 0.05. Therefore, the effect of these factors on the maximum force is meaningless. In other words, the differences in these factors do not create a statistically significant difference for the maximum force. However, the P value of the filling ratio (0.038) is less than 0.05. Thus, it was determined that this factor significantly affects the maximum force for L-joints. The R2 value, which shows the model's reliability, is 97.70%. The larger this value is, the higher the reliability of the analysis. Thus, it can be stated that this analysis is highly accurate.

Table 4. ANOVA results for maximum force

Factor	Contribution Rate (%)	P-Value
Nozzle Temperature (°C)	6.87	0.251
Fill Ratio (%)	57.95	0.038
Print Pattern	32.88	0.065

After ANOVA, regression analysis was performed, which gives the relationship between maximum force and printing parameters as an equation. The relationship between nozzle temperature filling ratio and maximum force depending on the printing pattern is specified by equation 2. With this equation, the maximum force of the L-joint element can be estimated without experimentation.

$$\begin{aligned}
&(\text{Grid})\ \text{Max. Force} = -176 + 0.692\ \text{Nozzle Temp.} + 4.336\ \text{Fill Ratio} \\
&(\text{Line})\ \text{Max. Force} = -138 + 0.692\ \text{Nozzle Temp.} + 4.336\ \text{Fill Ratio} \\
&(\text{Zigzag})\ \text{Max. Force} = -108 + 0.692\ \text{Nozzle Temp.} + 4.336\ \text{Fill Ratio}
\end{aligned} \tag{2}$$

Figure 9 shows the relationship between the maximum force estimated by the regression equation and the maximum force obtained in the experiments. This relationship is represented by equation 3. In the second-degree regression model, the R^2 value was determined as 84.43%. This value shows that the equation giving the relationship between the printing parameters and the maximum force effectively estimates the maximum force.

$$\text{Max. Force} = 204.3 - 0.3234\ (\text{Predicted Force}) + 0.002113(\text{Predicted Force})^2 \tag{3}$$

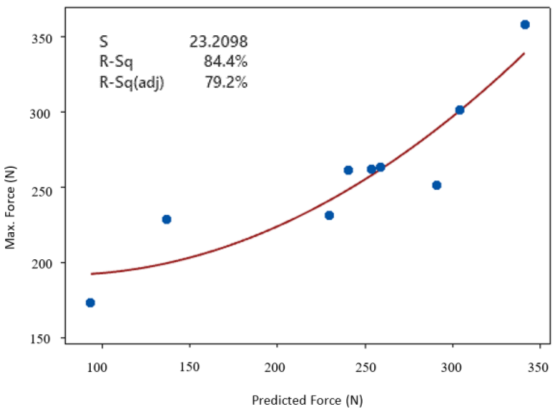

Figure 9. Second-degree regression model.

4. Conclusions

In this study, the effects of nozzle temperature (190, 200 and 210°C), filling ratio (50, 60 and 70%) and printing pattern (line, grid and zigzag) on the strength of L-joints were investigated. Optimum printing parameter values were determined using the Taguchi method. In addition, the contribution (effect) rate of printing parameters on the part strength was determined with ANOVA. The results obtained are listed below.

- A tensile test was applied to examine the strength of the samples produced at different printing parameters. As a result of the tensile test, the highest maximum force (358.4 N) was determined at 210°C nozzle temperature, 70% filling ratio and zigzag pattern.
- The lowest maximum force (173.5 N) was determined at 200°C nozzle temperature, 50% filling ratio and grid printing pattern.
- Due to the increase in nozzle temperature and filling ratio, parts with minimum gaps were produced with more material. This increased the strength of L-type samples.
- The zigzag printing pattern positively affected the strength by providing a more homogeneous load distribution on the part compared to other patterns.
- As a result of Taguchi analysis, optimum values for nozzle temperature, filling ratio and printing pattern were determined as 210°C, 70% filling ratio and zigzag pattern.
- In ANOVA, it was determined that the most effective parameter on the maximum force was the filling ratio, with a rate of 57.95%. The second most effective parameter was the print pattern, with a rate of 32.88%, and the least effective parameter was the nozzle temperature, with a rate of 6.87%.

As a result, it was determined that the printing parameters affected the strength of the L-joint samples. It was also emphasised that the quality and performance of the produced part could be improved by optimising these parameters.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	A.T.	C.G.D.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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