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THE APPLICATION OF THE TAGUCHI METHOD FOR OPTIMIZING THE COMPRESSION STRENGTH OF PLA SAMPLES PRODUCED USING FDM

FDM KULLANILARAK ÜRETİLEN PLA NUMUNELERİNİN BASMA MUKAVEMETİNİ OPTİMİZE ETMEK İÇİN TAGUCHİ YÖNTEMİ UYGULAMASI

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ABSTRACT

In this study, the Taguchi method was applied to optimize the compressive strength of PLA samples produced using Fused Deposition Modelling (FDM). The study used Taguchi L9 experimental design to optimize three different process parameters (wall thickness, filling pattern, and printing speed). S/N ratios and ANOVA methods were used to analyze the experiments. The results of the experiments using the Taguchi technique were analyzed according to S/N ratios and the parameter levels with the best results were determined. The best levels for wall thickness, filling pattern, and print speed parameters were determined and the effects of these parameters were analyzed. It was concluded that wall thickness was the most effective parameter and filling pattern and print speed were less effective. ANOVA analysis confirmed the influence of the parameters on the compressive strength. It was observed that wall thickness contributed the most (70.20%) and filling pattern contributed the second most (29.11%).

Keywords: Fdm, pla, compression strength, taguchi, anova

ÖZET

Bu çalışmada, Eriyik yığma modelleme (EYM) kullanarak üretilen PLA numunelerinin basma mukavemetini optimize etmek amacıyla Taguchi yöntemi uygulanmıştır. Çalışma, üç farklı işlem parametresini (duvar kalınlığı, dolgu deseni ve baskı hızı) optimize etmek için Taguchi L9 deney tasarımını kullanmıştır. Deneylerin analizi için S/N oranları ve ANOVA yöntemleri kullanılmıştır. Taguchi tekniği kullanılarak yapılan deneylerin sonuçları, S/N oranlarına göre analiz edilmiş ve en iyi sonuçlar elde edilen parametre seviyeleri belirlenmiştir. Duvar kalınlığı, dolgu deseni ve yazdırma hızı parametreleri için en iyi seviyeler belirlenmiş ve bu parametrelerin etkileri incelenmiştir. Duvar kalınlığının en etkili parametre olduğu ve dolum deseni ile baskı hızının ise daha az etkili olduğu sonucuna varılmıştır. ANOVA analizi, parametrelerin basma mukavemeti üzerindeki etkisini doğrulamıştır. Duvar kalınlığının en fazla katkı sağladığı (%70.20) ve dolgu deseninin ikinci yüksek katkı sağladığı (%29.11) görülmüştür.

Anahtar kelimeler: Eym, pla, basma dayanımı, taguchi, anova

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INTRODUCTION

Over the past twenty years, there has been a surging fascination with additive manufacturing (AM). Thanks to the swift progress of technology, AM has presented numerous prospects like heightened manufacturing velocity, the capacity to craft intricate structural designs, and diminished resource wastage (Kafshgar et al., 2021). AM, also known as 3D printing, involves the creation of components through a layer-by-layer production method using 3D model information. It is frequently the antithesis of subtractive manufacturing, where material is removed to shape objects (Hikmat et al., 2021). Numerous commercial additive manufacturing systems are currently available, including fused deposition modeling (FDM), direct metal deposition (DMD), 3D printing, selective laser sintering (SLS), inkjet modeling (IJM), and stereolithography (SLA). These systems vary in their layering techniques and the range of materials suitable for safe production (Mohamed et al., 2015)

FDM stands as a prominent illustration of additive manufacturing technology due to its capability to effortlessly produce intricate thermoplastic components within office settings. Stratasys Inc., located in the United States, pioneered FDM during the 1990s (Bakar et al., 2010). In recent times, the convenience of operation, affordability of machinery, and the robustness of components have contributed significantly to the advancement of FDM has the capability to fabricate prototypes using materials like acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) and similar plastics. In the FDM process, a heated, molten filament material is extruded after reaching its melting point, with the extrusion head maneuverable both horizontally and vertically via a numerically controlled mechanism. The nozzle adheres to a computer-aided manufacturing (CAM) software-controlled tool path, constructing the part layer by layer, starting from the bottom and working upward (Liu et al., 2017; Torres et al., 2015; Mohan et al., 2017). The capability of additive manufacturing technologies to allow the production of complex designs and thus to produce lightweight parts with several features and high specific strengths at the same time, has made their use widespread, especially in the aerospace industry, where the reduction of fuel consumption and emission characteristics is important (Başçı &Yamanoğlu, 2021).

Studies on the compressive strength of PLA materials with FDM technology and optimization techniques are listed below. The study by Sai et all. (Sai et al., 2020) concluded that the combined ANFIS-WOA methodology accurately determines the optimal FDM process parameters for PLA biomedical implant parts. This approach addresses critical concerns in additive manufacturing for customized biomedical applications by maximizing compressive strength while effectively minimizing surface roughness and build time. The study conducted by Sood et al.(Sood et al., 2012) elucidated that the optimization of process variables, such as layer thickness, part orientation during formation, scanning angle, scanning width, and air gap, has a substantial impact on the enhancement of compressive stress resistance in the domain of FDM manufacturing. They developed a validated prediction equation and used quantum behavior particle swarm optimization (QPSO) to determine the optimal parameter settings. In addition, artificial neural networks (ANN) were used to predict the compressive stress, and the complex non-linear relationship between process parameters and results was demonstrated. Darbar and Patel's study (Darbar & Patel, 2017) concluded that in FDM for rapid prototyping, the quality of prototypes is significantly influenced by key process parameters, specifically layer thickness, part build orientation, and raster width. They utilized Taguchi's method, ANOVA, and Artificial Neural Networks (ANN) to assess these parameters. The research confirmed that increasing layer thickness and decreasing part build orientation led to improved mechanical properties and surface quality. They attributed the weakness in FDM parts' strength to potential distortion within or between layers caused by temperature gradients during the printing process. Lee et al.'s research (Lee et al., 2007) highlighted the significance of material property measurements in predicting the mechanical behavior of Rapid Prototyping (RP) parts. They characterized each RP process, including FDM, 3D printing, and the nanocomposite deposition system (NCDS), based on specific process parameters. Their study involved fabricating specimens to assess compressive strengths, revealing anisotropic properties in most cases. Dixit and Jain's study (Dixit & Jain, 2022) concluded that in the context of Fused Filament Fabrication (FFF) for lattice structure fabrication, optimizing process parameters is crucial for enhancing compressive strength. They employed the Taguchi method and examined two different materials (TPU and PLA). Their research revealed that a layer thickness of 0.1 mm, infill density of 100%, and a printing speed of 40 mm/s represented the optimal parameter combination for maximizing compressive strength. Hsueh et al. (Hsueh et al., 2021) concluded that PLA and PETG materials in FDM exhibit distinct mechanical behavior under different loading conditions, temperatures, and speeds. Higher printing temperatures generally enhance mechanical properties (tension, compression, bending) for both materials, though speed impacts vary. While PLA generally exhibits superior mechanical properties compared to PETG, PETG fares better in terms of thermal deformation.

In the literature review, the insufficiency of studies especially related to the wall thickness parameter drew attention. The focus of this research revolves around the optimization of process variables to achieve the highest compressive strength for cylindrical components produced in accordance with the ASTM D695-15 standard. The Taguchi orthogonal array technique has been employed for experiment design, while the analysis of experiment accuracy is conducted through Signal-to-Noise (S/N) ratio and Analysis of Variance (ANOVA). Three distinct process variables have been chosen for this study, namely wall thickness, filling pattern, and printing speed.

MATERIAL & METHOD

In this research, we utilized Creality's CR-PLA filament in a vibrant red hue as our testing material. The filament's diameter measured 1.75 mm. Printing procedures were executed using the Creality Ender-3 S1 Pro 3D printer, which operates on the Fused Deposition Modeling (FDM) technology. This 3D printer boasts a printing volume of 220 x 220 x 270 mm. The printer is equipped with a maximum nozzle temperature of 300 °C, and a maximum bed temperature of 110 °C, and can achieve a maximum printing speed of 150 mm/s. The printing operations were conducted using a 0.4 mm diameter nozzle.

The Taguchi method was the chosen approach for optimizing parameters in this investigation. Following Taguchi's L9 design, we established three variable parameters, each with three different levels. These selected parameters encompass wall thickness, filling pattern, and printing speed, with a comprehensive breakdown of their values provided in Table 1. Additionally, Table 2 outlines the parameters that remained consistent throughout the experimental procedures.

Table 1. Printing Parameters and Levels

Factors	Unit	DoF	Level 1	Level 2	Level 3
Wall Thickness	mm	2	0.4	0.8	1.2
Filling Pattern	---	2	Cubic	Gyroid	Zig Zag
Print Speed	mm/s	2	25	50	75
Total DoF	---	6	---	---	---

Table 2. Constant Experimental Parameters

Layer Height (mm)	0.2
Top/Bottom Thickness (mm)	0.4
Infill Density (%)	30
Printing Temperature (°C)	210
Built Plate Temperature (°C)	60
Fan Speed (%)	100

Minitab 20.3 software was used in the experimental design and application of the Taguchi method. The L9 experimental design with three parameters and three levels is shown in Table 3. Taguchi analyses and variance (ANOVA) analyses were performed in Minitab 20.3. Taguchi analyses were performed using equation 1 according to the larger is better principle (Demir & Yüksel, 2023).

Table 3. Taguchi L9 Orthogonal Experiment Design

Experiment Number	Wall Thickness (mm)	Filling Pattern	Print Speed (mm/s)
1	0.4	Cubic	25
2	0.4	Gyroid	50
3	0.4	Zig Zag	75
4	0.8	Cubic	50
5	0.8	Gyroid	75
6	0.8	Zig Zag	25
7	1.2	Cubic	75
8	1.2	Gyroid	25
9	1.2	Zig Zag	50

$$\frac{S}{N_{max}} = -10log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

It was designed in the Solidworks 2020 drawing programme with compression specimens in accordance with ASTM D695-15 standard (Nathaphan & Trutassanawin, 2021). The cylindrical specimens produced according to this standard have a diameter of 12.7 mm and a length of 25.4 mm. The designed specimens were transferred to the Ultimaker Cura 5.4.0 slicing programme. This programme helps us to set the printing parameters precisely. Three samples were printed for each experimental group. UTEST brand tensile-compression device was used in compression tests. The experiments were carried out at room temperature with a constant feed rate of 5 mm/min. The experimental results were calculated as the average of three specimens for each group and standard deviations were also considered. Printing specimens and specimens applied compression test in the compression device are shown in Figure 1.

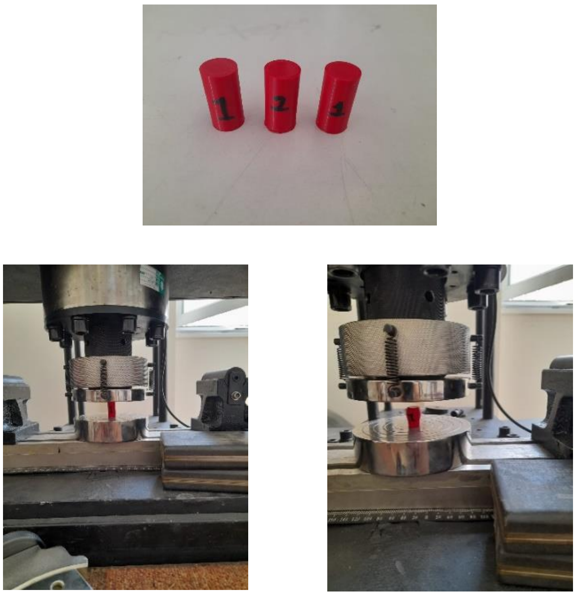

Figure 1. Compression Specimens Used in the Experiments

RESULTS & DISCUSSION

The compressive strengths and standard deviations obtained following the compression test are given in Table 4. Compressive strengths were determined by averaging three specimens. Signal to noise ratios (S/N) calculated according to Taguchi analysis are also given in Table 4. When Table 4 is analyzed, it is seen that the lowest compressive strength is 11.4 MPa in sample 1 and the highest compressive strength is 34.5 MPa in sample 9. The compressive strength of sample 9 with the highest compressive strength is 202.6% higher than that of sample 1 with the lowest compressive strength. Such a high rate of change in compressive strength with parameter variation shows that the variation of the selected parameters has a very effective role in compressive strength.

Table 4. Compression Strength Values with the Calculated S/N Ratios

No	Compression Strength (MPa)	Standard Deviation	S/N Ratio
1	11.4	0.21	21.12
2	13.6	0.51	22.67
3	20.0	0.39	26.02
4	21.5	0.12	26.63
5	20.5	0.44	26.23
6	28.6	0.44	29.13
7	26.2	0.16	28.36
8	26.2	0.59	28.36
9	34.5	0.48	30.76

According to the S/N ratios, the response table created according to the larger is better principle is shown in Table 5. In the table, the largest values selected within three levels for each parameter give the optimum parameter levels. In this case, level 3 is the optimum parameter for all parameters. The values given with delta in the table give the importance of the parameters. Parameters with higher delta values were more effective. The values shown with rank give the order of importance of the parameters. In this direction, it is seen that the most effective parameter is wall thickness. The order of importance of the parameters is as follows: wall thickness, filling pattern, and print speed. The variation of S/N ratios with parameters and levels is also displayed in Figure 2.

Table 5. Table of Results Showing the S/N Ratios for Compressive Strength (Larger Is Better)

Level	Wall Thickness	Filling Pattern	Print Speed
1	23.27	25.37	26.20
2	27.33	25.75	26.69
3	29.16*	28.64*	26.87*
Delta	5.89	3.27	0.67
Rank	1	2	3

*Optimum level

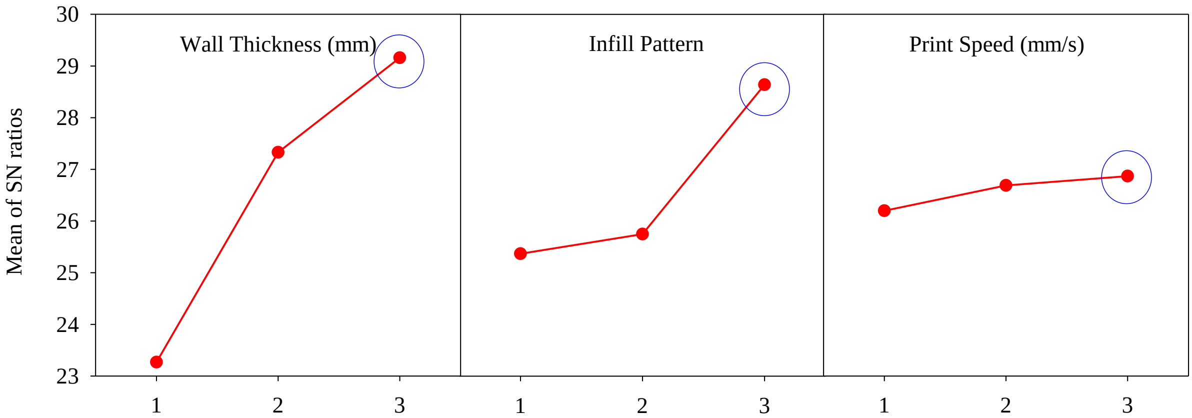

Figure 2. S/N Ratio Graph of Parameters for Compression Strength

Analysis of variance (ANOVA) was performed to understand the effect of the parameters on the compressive strength, which is the output of the experiment. ANOVA analyses were performed at a 95% confidence interval. Table 6 shows the results of the ANOVA analysis. When the P-Value is less than 0.05, it means that the parameters are effective. According to the contribution rates in Table 6, the most effective parameter was wall thickness with 70.20% and the second effective parameter was filling pattern with 29.11%. The contribution of print speed was very low only 0.53%. The residual error is 0.16%. The fact that the residual error is so low shows the reliability of the results. In addition, the pie chart in Figure 3 is also given for a better understanding of the contribution of the parameters on the compressive strength.

Table 6. ANOVA Findings for Compression Strength S/N Ratios

Source	(DoF)	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
Wall Thickness	2	296.996	148.498	429.290	0.002	70.20
Filling Pattern	2	123.153	61.576	178.010	0.006	29.11
Print Speed	2	2.262	1.131	3.270	0.234	0.53
Residual Error	2	0.692	0.346	---	---	0.16
Total	8	---	---	---	---	100

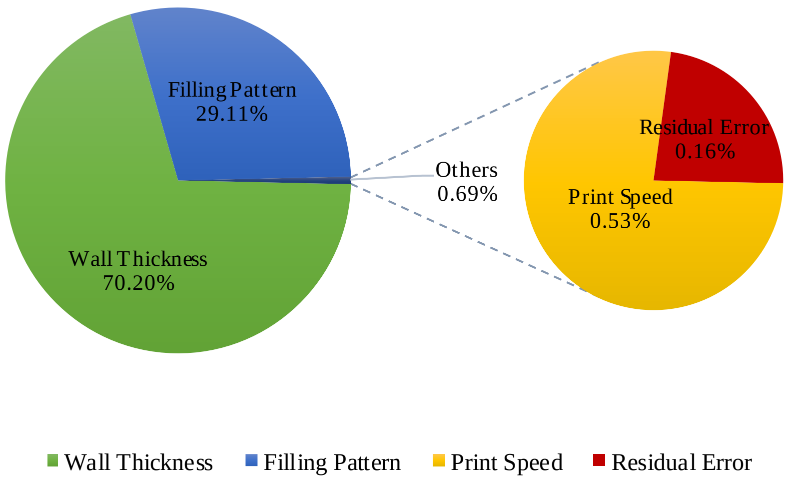

Figure 3. Effect of Parameters on Compression Strength as a Percentage

The optimum experiment was determined as wall thickness: 1.2 mm, filling pattern: Zig Zag, and printing speed: 75 mm/s. The prediction obtained using the Taguchi technique was made by the Minitab program, which provides this effect (Table 7). The estimated compressive pressure remains constant at 33.91 MPa. Samples were produced according to the optimum effect and their compressive strength was also tested. According to the experimental value, the compression limit is 34.74 MPa. This value differed from the predicted value by 2.45%. The compressive strength value of 34.74 MPa tested according to the optimum effect is 0.7% higher than the 34.5 MPa tested in sample number 9 in previous tests.

Table 7. Optimal Outcomes and Validation Experiment Findings.

Optimum Level: Wall Thickness 3	**Predicted Value (MPa)**	**Experimental Result (MPa)**
Filling Pattern 3 Print Speed 3	33.91	34.74
Prediction Error (%)	2.45	

Table 8 shows the regression equations created for the prediction of compressive strength. While wall thickness and print speed are continuous predictors, filling pattern is a categorical predictor. For this reason, three different linear regression equations were created with the change of the filling pattern. The purpose of creating these equations is to provide the opportunity to make predictions for intermediate values without experimenting. The R^2 value of the equations is a very high value of 98.17%. This shows that the predictive ability of the equations is very high.

Table 8. Equations for Prediction of Compression Strength

	Compression Strength (MPa)
Cubic	Compression Strength = 5.56 + 17.43*wall thickness + 0.0033*print speed
Gyroid	Compression Strength = 5.99 + 17.43*wall thickness + 0.0033*print speed
Zig Zag	Compression Strength = 13.60 + 17.43*wall thickness + 0.0033*print speed
R-sq= 98.17%	

The linear regression equation showing the relationship between the predicted compressive strengths (Table 8) and the compressive strength values obtained from the tests are shown in Table 4. In Figure 4, CI indicates confidence interval and PI indicates predict interval. The R^2 value of the equation is very high as 98.2%. This shows that the predicted values and experimental values are consistent.

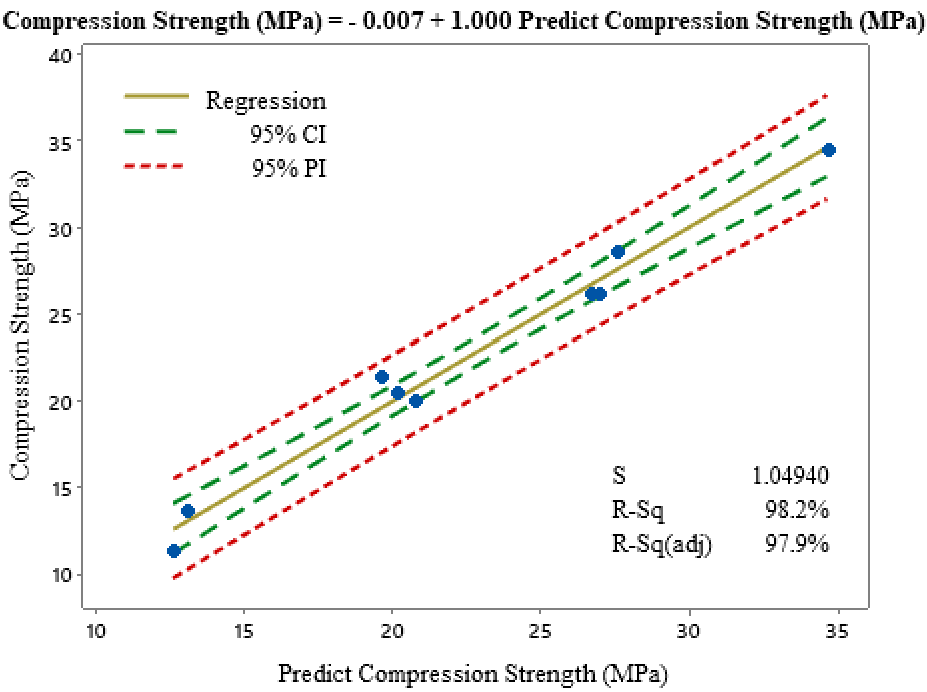

Figure 4. Linear Regression Model Compared with Experimental Results for Compression Strength

CONCLUSIONS

In summary, this study thoroughly investigated the influence of various parameters on compressive strength in 3D printing. The analysis revealed a substantial variation in compressive strength across samples, with the highest strength in sample 9 surpassing the lowest in sample 1 by a remarkable 202.6%. The Taguchi analysis and S/N ratios identified optimal parameter levels at level 3 for all factors, with wall thickness emerging as the most influential, followed by filling pattern and print speed.

ANOVA analysis confirmed the significance of these parameters, with wall thickness contributing the most (70.20%), followed by filling pattern (29.11%), while print speed had minimal impact (0.53%). The low residual error underscored the results' reliability. The Taguchi technique led to the determination of the optimum parameters: wall thickness (1.2 mm), filling pattern (Zig Zag), and printing speed (75 mm/s), resulting in a predicted compressive strength of 33.91 MPa. Experimental testing validated this prediction at 34.74 MPa, deviating by only 2.45%.

Highly accurate regression equations were developed (R^2 = 98.17%), allowing predictions for various parameters without further experimentation. The strong correlation (R^2 = 98.2%) between predicted and experimental values underscores the validity of our models. This research provides crucial insights into optimizing 3D printing processes for desired material strength.

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