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Analysis and Optimization of Process Parameters Affecting on the Tensile Strength of PLA and Iron-Reinforced PLA Samples Fabricated by Fused Deposition Modeling Method

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ABSTRACT

This study focuses on investigating the influence of printing parameters on the tensile strength of PLA and iron-reinforced PLA samples produced using FDM technology. Filament material (PLA and iron-reinforced PLA), infill ratio (20, 40 and 60%), layer thickness (0.1, 0.2 ve 0.3 mm), printing speed (40, 60 and 80 mm/s) and raster angle (30, 45 and 60°) were selected as process parameters. The experimental design was based on the Taguchi L18 index. Signal-to-Noise (S/N) ratio, variance analysis (Anova) and regression analyses were used to statistically analyze the tensile strength values obtained as a result of experimental measurements. The outcomes of this study show that the reinforcement to PLA material decreases the tensile strength and increases the % elongation. The maximum tensile strength was measured as 33.55 MPa at 60% infill rate, 0.3 mm layer thickness, 60 mm/s printing speed and 60° raster angle in PLA filament material, which is the optimum process parameters.

Eriyik Yığma Modelleme Yöntemi ile Üretilen PLA ve Demir Takviyeli PLA Numunelerinin Çekme Dayanımını Etkileyen Proses Parametrelerinin Analizi ve Optimizasyonu

MAKALE BİLGİSİ

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Anahtar Kelimeler:
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ÖZET

Bu çalışma, FDM teknolojisi kullanılarak üretilen PLA ve demir takviyeli PLA numunelerin çekme mukavemeti üzerinde baskı parametrelerinin etkisini araştırmaya odaklanmaktadır. Proses parametreleri olarak filament malzemesi (PLA ve demir takviyeli PLA), dolgu oranı (20, 40 ve 60%), katman kalınlığı (0.1, 0.2 ve 0.3 mm), baskı hızı (40, 60 ve 80 mm/s) ve tarama açısı (30, 45 ve 60°) seçilmiştir. Deney tasarımı Taguchi L18 indeksine göre yapılmıştır. Deneysel ölçümler sonucunda elde edilen çekme dayanımı değerlerini istatistiksel olarak analiz etmek için Sinyal Gürültü (S/N) oranı, varyans analizi (Anova) ve regresyon analizleri kullanılmıştır. Bu çalışmanın sonuçları PLA malzemeye demir takviyesinin çekme dayanımını düşürdüğünü ve % uzamayı arttırdığını göstermektedir. Maksimum çekme dayanımı optimum proses parametreleri olan PLA filament malzemesinde, 60 doluluk oranında, 0.3 mm katman kalınlığı, 60 mm/s baskı hızında ve 60° tarama açısında 33.55 MPa olarak ölçülmüştür.

1. INTRODUCTION (GİRİŞ)

Today, Fused Deposition Modeling (FDM) technology has become a widely used technique to produce complex-shaped parts that are difficult to manufacture due to its advantages over traditional methods [1]. Unlike traditional manufacturing methodologies where a final small design is achieved by removing material from a large part, FDM allows complex shapes to be created with

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less material waste by combining materials layer upon layer [2, 3]. This technology can help increase industrial productivity and reduce production costs by reducing time-to-market [4]. Due to these superior aspects, its use in industrial applications such as aerospace, automotive, medical, and construction, is becoming widespread [3-5]. In addition, this method can produce 40-60% lighter and structurally robust products for applications where weight savings are critical [6]. Thermoplastic polymers are utilized in this technique as construction materials [7]. The type of construction materials has a significant impact on print quality and mechanical properties. The quality and mechanical properties of the printed samples are also influenced by several process variables such as layer thickness, raster angle, infill percentage, extruder temperature, bed temperature, printing speed and extrusion [8]. Günay et al. applied the Taguchi method to investigate the effect of printing parameters on the tensile strength of PLA+ material fabricated by FDM technology [9]. Their results showed that the most effective parameter on the tensile strength was the fill rate, and the scanning angle and printing speed were the other important parameters, respectively. Roa et al. investigated the effect of printing parameters such as layer thickness, print temperature, and infill pattern on the tensile strength of carbon fiber PLA [10]. The results showed that the interaction between layer thickness and infill pattern has a significant effect on the tensile strength of carbon fiber PLA. Kamer et al. investigated the mechanical properties of ABS and PLA material fabricated with different printing speeds by FDM technology [11]. As a result, the authors indicated that the tensile strength of the samples produced with PLA material is higher than the samples produced with ABS material. Altan et al. [12] investigated the effects of process parameters on the quality of PLA composites produced by FDM method and reported tensile strength and surface quality of the FDM samples improved by about 25% and 12%, respectively at optimal process conditions. Schirmeister et al. investigated the effects of printing parameters such as temperature and diameter of the nozzle, extrusion rate, build plate temperature, and build plate material on the mechanical properties and surface quality of samples produced using HDPE (high density polyethylene) [13]. The authors reported that the nozzle diameter and printing speed affect the surface quality but not the mechanical properties. Sammaiah et al. investigated the influence of process parameters on the surface quality of ABS composites produced by FDM [14]. The results showed that the surface roughness values increased with the increase of the layer thickness and decreased with the increase of the filling density. Liu et al. investigated the effects of wood, ceramic, metal, and carbon fiber reinforcements on the mechanical characteristics of PLA composites fabricated by FDM method [15]. The authors reported that ceramic, copper, and aluminum-based PLA composite samples exhibit similar mechanical properties to PLA samples. Zhang et al. studied the characterization of the mechanical properties of PLA and copper/PLA composite part produced by FDM method [16]. As a result, they observed that copper reinforcement decreased the tensile strength and increased the % elongation compared to PLA material.

In this study, it is aimed to compare the tensile strength of PLA and iron reinforced PLA composites produced using fused deposition modeling (FDM) at different printing parameters. In this context, tensile samples have been produced using the Taguchi L18 orthogonal array. Analysis of the Signal-to-Noise (S/N) ratio, variance analysis (ANOVA) and regression analysis have been used in statistical evaluation of the data obtained as a result of tensile tests. Finally, the validation of the optimization has been checked by verification tests.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

In this study, it is aimed to analyze the effect of filament materials and process parameters on the mechanical properties of tensile specimens produced by the FDM method. In this context, tensile specimens conforming to ASTM D638-IV standards have been produced using PLA and iron-reinforced PLA filaments with Zaxe brand 3D printer. These filaments, which are suitable for production by the fused deposition modeling (FDM) method, were commercially available from Zaxe. The printing temperature and table temperature were selected as 210°C and 40°C, considering the manufacturer's recommendation. Figure 1 shows the experimental set. Three different fill rates (20, 40 and 60%), three different layer thicknesses (0.1, 0.2 and 0.3 mm), three different printing speeds (40, 60 and 80 mm/s) and three different raster angles (30°, 45° and 60°) were selected as process parameters. According to these parameters, tensile specimens were produced using the Taguchi L18 orthogonal array. Tensile tests were carried out on an INSTRON brand test device (Instron Corp., Canton, MA, USA) with a capacity of 100 kN.

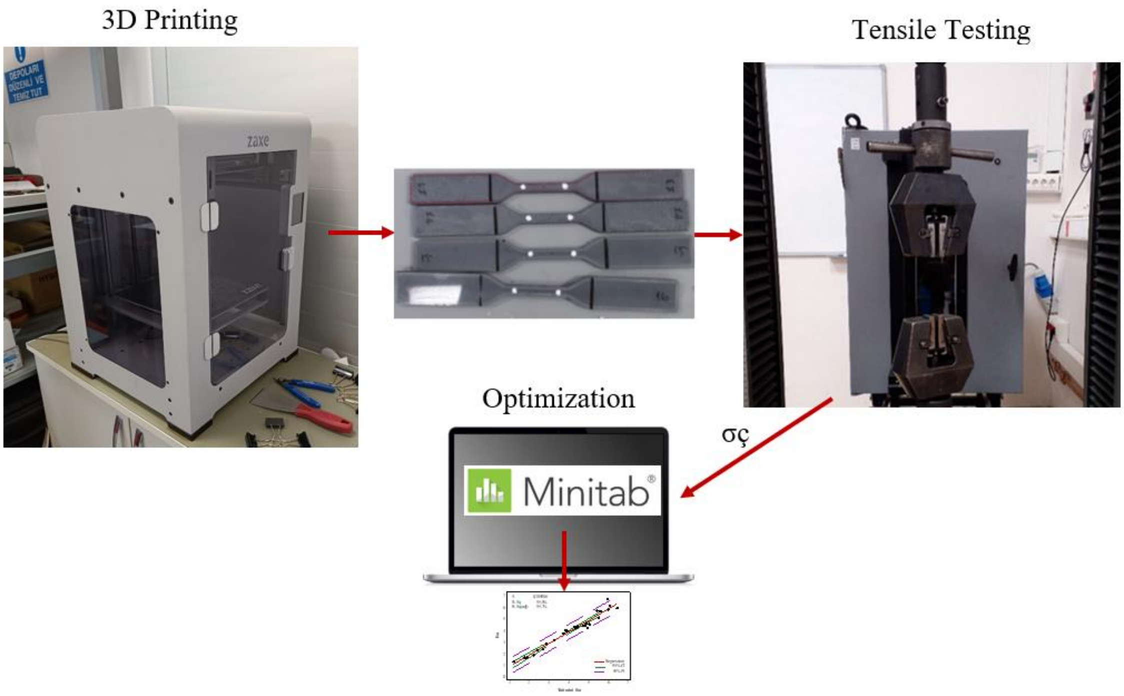


Figure 1. Experimental setup (Deney düzeneği)

In the optimization process, filament material (A), infill ratio (B), layer thickness (C), printing speed (D), and raster angle (E) were selected as input factors while tensile strength was selected as output parameters. Analysis of variance (ANOVA) and regression analyses were used to explain and model the relationship between tensile strength values obtained from experimental measurements and process parameters, respectively [17, 18]. The "largest best" approach in Equation 1 was used to determine the maximum tensile strength value.

$$n = \frac{\mathrm{S}}{\mathrm{N}} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{yi^2}\right) \tag{1}$$

3. EXPERIMENT AND OPTIMIZATION RESULTS (DENEY VE OPTİMİZASYON SONUÇLARI)

3.1. Analysis of the Signal-to-Noise (S/N) ratio (Sinyal-Gürültü (S/N) Oranı Analizi)

The tensile strength values of the samples produced with PLA and iron-reinforced filaments at different printing parameters and the corresponding S/N values for each printing combination and S/N analysis response results are given in Table 1 and Table 2, respectively. In Table 2, the highest value for each process factor indicates the optimum level of control. From this table, the optimal combination of process parameters for maximum tensile strength is found to be: A2B3C3D2E3. The symbols A, B, C, D and E represents process parameters: filament material, infill ratio, layer thickness, printing speed, and raster angle, respectively. Figure 2 shows the scatter plot of process parameters on the average S/N ratio. In this graph, the point where the S/N ratio is the highest for each process parameter indicates the optimum level.

Table 1. Results of the experiment (Deney sonuçları)

Test Id	Parameters						
	A	B	C	D	E	Tensile strength (MPa)	Tensile strength *S/N (dB)*
1	Iron-reinforced PLA	20	0.1	40	30	10.82	20.684
2	Iron-reinforced PLA	20	0.2	60	45	11.92	21.525
3	Iron-reinforced PLA	20	0.3	80	60	12.35	21.833
4	Iron-reinforced PLA	40	0.1	40	45	15.43	23.767
5	Iron-reinforced PLA	40	0.2	60	60	16.04	24.104
6	Iron-reinforced PLA	40	0.3	80	30	16.19	24.184
7	Iron-reinforced PLA	60	0.1	60	30	19.06	25.602
8	Iron-reinforced PLA	60	0.2	80	45	19.11	25.625
9	Iron-reinforced PLA	60	0.3	40	60	19.54	25.818
10	PLA	20	0.1	80	60	24.86	27.910
11	PLA	20	0.2	40	30	25.14	28.007
12	PLA	20	0.3	60	45	25.89	28.262
13	PLA	40	0.1	60	60	27.85	28.896
14	PLA	40	0.2	80	30	28.12	28.980
15	PLA	40	0.3	40	45	28.36	29.054
16	PLA	60	0.1	80	45	32.28	30.178
17	PLA	60	0.2	40	60	33.10	30.396
18	PLA	60	0.3	60	30	33.55	30.513

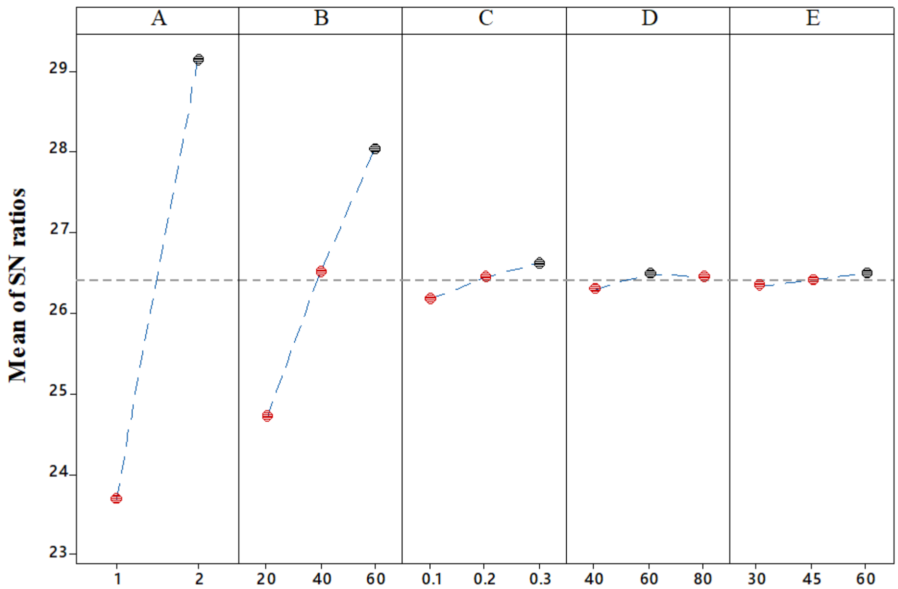


Figure 2. Distribution of process parameters on average S/N ratio (Ortalama S/N oranı üzerinde proses parametrelerinin dağılımı)

Table 2. ANOVA results for tensile strength (Çekme dayanımı için ANOVA sonuçları)

Level	**A**	**B**	**C**	**D**	**E**
1	23.68	24.70	26.17	26.29	26.33
2	**29.13**	26.50	26.44	**26.48**	26.40
3		**28.02**	**26.61**	26.45	**26.49**
Delta	5.45	3.32	0.44	0.20	0.16
Rank	1	2	3	4	5

As a result, the maximum tensile strength value was measured as 33.55 MPa at 60% infill rate, 0.3 mm layer thickness, 60 mm/s printing speed and 60° raster angle in PLA filament material, which is the optimum process parameters.

3.2. Evaluation of Tensile Test Results (Çekme Testi Sonuçlarının Değerlendirilmesi)

Figure 3 shows the variation of tensile strength of the samples produced with PLA and iron-reinforced PLA filament materials at different printing parameters. When Figure 3 is examined, it is seen that the tensile strengths increase with the increase in the filling ratio and layer thickness for the two filament materials. Günay et al. associated the increase in tensile strength with the increase in the filling ratio with the increase in the tensile load carrying capacity per unit area as a result of the increase in the filling ratio in the cross-sectional area [9]. According to the general trend, the tensile strength of both filament materials increased slightly with the increase in printing speed but showed a decreasing trend after 60 mm/s press speed. Raster angle, on the other hand, does not seem to have a significant effect on the tensile strength.

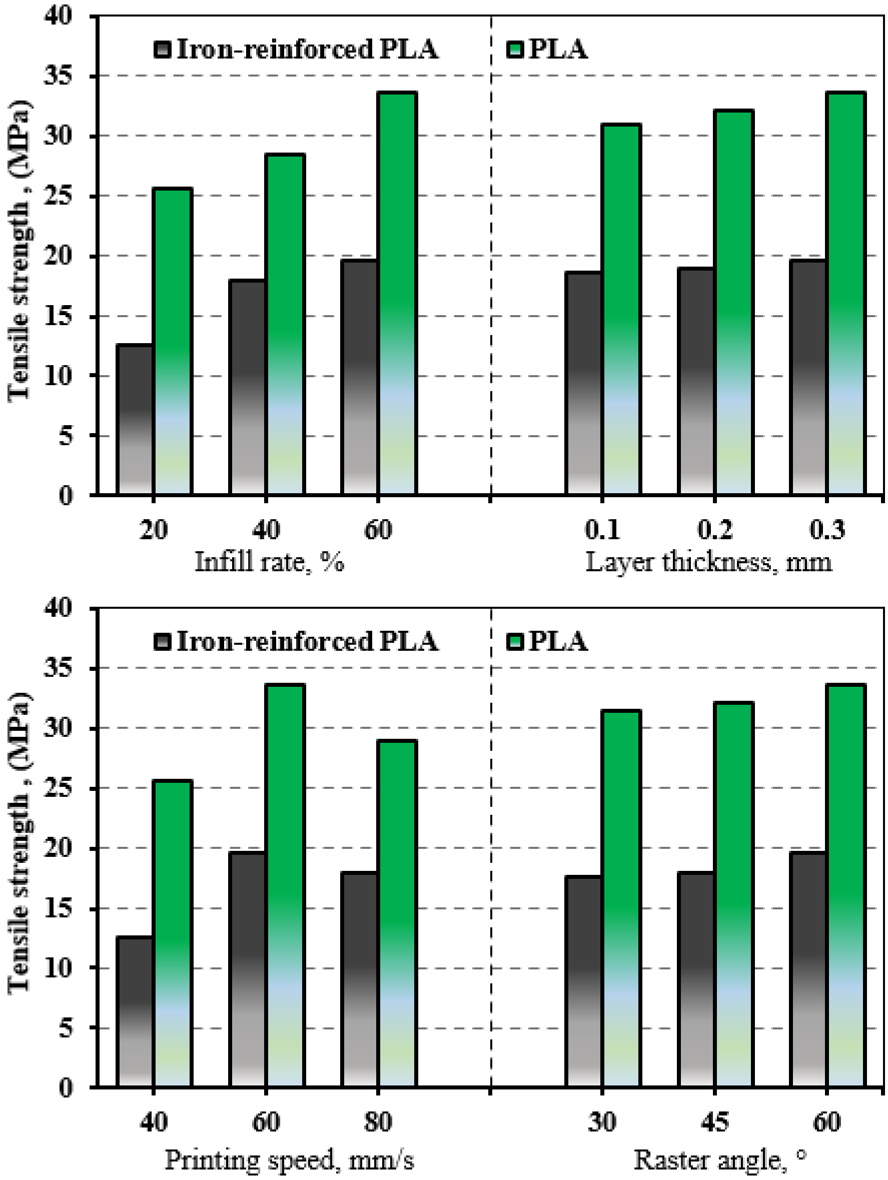
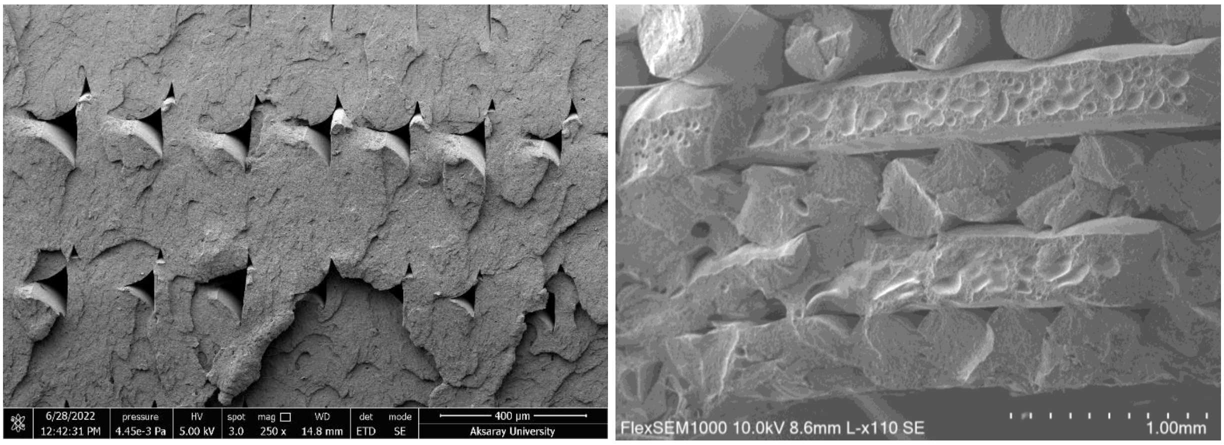


Figure 3. Variation of tensile strength according to proses parameters (Proses parametrelerine göre çekme dayanımının değişimi)

On the other hand, it is clearly seen that the filament material plays an effective role on the tensile strength. The tensile strength values measured in PLA filament are higher than the tensile strength values obtained in iron-reinforced PLA filament under all printing conditions. In a similar study, Uzun and Erdoğdu reported that the tensile strength of the carbon and copper-doped samples was lower than the PLA samples [19]. Moreover, Özsoy et al. reported that PLA specimens had higher strength values than ABS specimens and explained this with the fact that the bonding between the layers during the specimen production process was better for PLA material specimens than ABS specimens [20]. Figure 4 shows the SEM images taken from the fracture surfaces of the specimens after the tensile test. When Figure 4 is examined, it is seen that the top and bottom layers adhere perfectly to each other for all filaments, but there are more air pockets and porous structures containing voids between the layers in the iron-doped PLA sample compared to the PLA sample. The formation of these porous structures is thought to be the cause of the decrease in the tensile strength of the iron-reinforced PLA sample. In short, iron reinforcement reduces tensile strength and increases % elongation compared to PLA material.



(a) (b)

Figure 4. SEM fracture surface images of a) PLA and b) Iron-reinforced PLA samples (a) PLA ve b) Demir takviyeli PLA numunelerin SEM kırık yüzey görüntüleri)

3.3. Analysis of Variance Results (Varyans Analizi Sonuçları)

ANOVA is a statistical technique used to detect how each of the control elements in the test design interacts with output parameters [17]. In this study, ANOVA was used to analyze the individual interaction of each process parameter on tensile strength. This analysis was performed at 5% significance level and 95% confidence level [17, 21-23]. ANOVA results for tensile strength are given in Table 3. The importance levels of the process parameters were determined by considering the F values in Table 3. The last column of the table shows the percentage value of the level of influence of each process parameter. According to Table 3, the percentage effects of factors A, B, C, D and E on the surface roughness were found to be 81.35%, 18.10%, 0.27%, 0.03% and 0.01%, respectively. The error percentage was quite low at 0.24%. As a result, the most important process factor affecting the tensile strength with 81.35% additive ratios is the filament material.

Table 3. ANOVA results for tensile strength (Çekme dayanımı için ANOVA sonuçları)

Source	DF	SS	MS	F	P	Contribution *(%)*
A	1	782.629	782.629	2682.98	0.000	81.35
B	2	174.104	87.052	298.43	0.000	18.10
C	2	2.608	1.304	4.47	0.050	0.27
D	2	0.329	0.164	0.56	0.590	0.03
E	2	0.073	0.037	0.13	0.884	0.01
Error	8	2.334	0.292	-	-	0.24
Total	17	962.076	-	-	-	100

3.4. Regression Analysis of Tensile Strength (Çekme Mukavemetinin Regresyon Analizi)

Regression analysis was applied to numerically express the relationship between the tensile strength of PLA and iron-reinforced PLA samples produced by FDM method and process parameters. The equations developed with the linear regression model to predict the tensile strength of PLA and iron-reinforced PLA specimens are given below, respectively.

$$\sigma_\tau = 19.909 + 0.19025\,B + 4.65\,C + 0.00217\,D + 0.00478\,E \tag{2}$$

$$\sigma_\tau = 6.722 + 0.19025\,B + 4.65\,C + 0.00217\,D + 0.00478\,E \tag{3}$$

The R^2 value for the tensile strength prediction equations developed through linear regression analysis was 0.968. The prediction equations, which have a very high coefficient of determination (R^2), produce values close to the true values and this is also confirmed by the comparison plot for the test results and predicted values given in Figure 5. Validation experiments are very important to see the success of the developed prediction equations and the optimization process. In this context, the confidence interval (CI) value for tensile strength was calculated using Equations 4 and 5.

$$n_{eff} = \frac{N}{1+T_{dof}} \tag{4}$$

$$CI = \sqrt{F_{a,1,fe}\, V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \tag{5}$$

The symbols N, Tdof, $F_{\alpha,1fe}$, α, fe, Ve, R and n_{eff} represents the total number of experiments, the total main factor degrees of freedom, the F ratio at a 95% confidence, the significance level, the degrees-of-freedom of error, error variance, the effective number of replications and the number of replications for confirmation experiments, respectively [24, 25]. The confidence interval was calculated as 1.554. According to the signal-to-noise (S/N) ratio analysis, the optimum factor group giving the highest tensile strength value was obtained as A2B3C3D2E3. the average value of the tensile strength was calculated to be 22.2 MPa.

$$\sigma\tau_{opt} = (A_2 - T_{\sigma\tau}) + (B_3 - T_{\sigma\tau}) + (C_3 - T_{\sigma\tau}) + (D_2 - T_{\sigma\tau}) + (E_3 - T_{\sigma\tau}) + T_{\sigma\tau}$$

$$[\sigma\tau_{opt} - CI] < \sigma\tau_{exp} < [\sigma\tau_{opt} + CI] = [33.43 - 1.554] < 33.55 < [33.43 + 1.554] = 31.876 < 33.55 < 34.984$$

As a result, the tensile strength values are within the confidence interval limits and accordingly, optimization of the process parameters has been performed at a significance level of 0.05. Furthermore, the accuracy of the optimization process have been tested at optimum levels and random levels for tensile strength. The validation results are given in Table 4. The error percentages calculated for the tensile strength are within acceptable limits and this indicates a successful optimization.

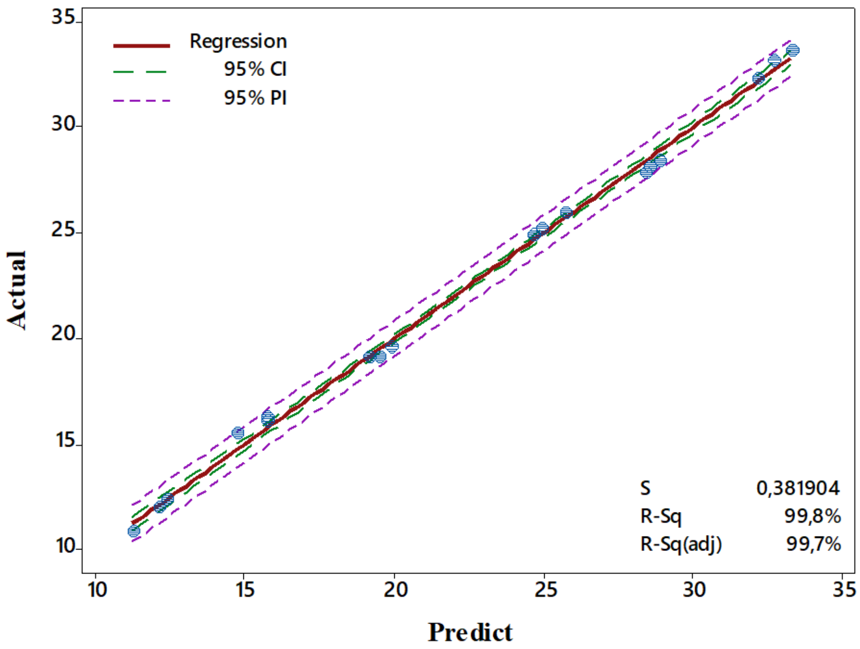


Figure 5. Comparison of the prediction results with experimental results (Tahmin sonuçlarının deneysel sonuçlarla karşılaştırılması)

Table 4. Validation test results (Doğrulama testi sonuçları)

	Actual	**Predict**	**Error (%)**
$A_2B_3C_3D_2E_3$ (optimum)	33.55	33.13	1.25
$A_2B_2C_2D_2E_1$ (random)	28.12	28.72	2.13

4. CONCLUSIONS (SONUÇLAR)

In this study, the effects of printing parameters such as infill rate, layer thickness, printing speed and raster angle on the tensile strength of PLA and iron-reinforced PLA specimens produced by fused deposition modeling technology were investigated experimentally and statistically. The results obtained from this study are summarized below:

- The optimal printing parameters for the tensile strength were determined as A2B3C3D2E3 (i.e., filament material = PLA, infill rate = 60%, layer thickness = 0.3 mm, printing speed = 60 mm/s and raster angle = 60°).
- According to the results of statistical analyses, the filament material plays an important role in tensile strength with a percentage contribution of 81.35%.
- The equation developed to predict the tensile strength of the samples produced using the 3D printer gives results very close to the actual values with an R^2 value of 0.968.
- It was observed that iron reinforcement of PLA material decreased the tensile strength and increased the % elongation.

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