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Araştırma Makalesi–Research Article

Optimization of Welding Parameters of AISI 431 and AISI 1020 Joints Joined by Friction Welding Using Taguchi Method

Taguchi Yöntemi Kullanılarak Sürtünme Kaynağı ile Birleştirilen AISI 431 ve AISI 1020 Bağlantılarının Kaynak Parametrelerinin Optimizasyonu

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ABSTRACT

Martensitic stainless steel AISI 431 and low carbon steel AISI 1020 are materials used together in many different industries. However, important problems are encountered when welding (fusion welding) these materials to each other. For this reason, friction welding process (Solid-state welding) is used to join these dissimilar metals. There are very few studies on joining these materials with friction welding. Therefore, the optimization of the welding parameters used in joining these dissimilar steel pairs with friction welding is of great important. In addition, the effects of the factors dependent on friction welding parameters need to be well understood. In this study, AISI 431 and AISI 1020 steel bars were successfully joined by friction welding, and the effects of welding parameters on tensile strength and axial shortening were investigated, and welding parameters were optimized using Taguchi method to obtain quality weld joints. The experimental results of the study showed that the highest tensile strength (573.32 MPa) of the joints was 54.53%, higher than the lowest tensile strength (370.99 MPa), the highest axial shortening (23.18 mm) was 650.16%, higher than the lowest axial shortening (3.09 mm). The optimal parameters for average axial shortening and average tensile strength were determined as A3B1C3 and A3B3C2; and the highest percentage contribution values for axial shortening and tensile strength were found to be 51.55% (rotating speed) and 63.90% (rotating speed); and R^2 values for the average axial shortening and average tensile strengths were found to be 97% and 99.3%, respectively.

Keywords- Friction Welding, Optimization, Taguchi Method, AISI 431, AISI 1020

ÖZ

Martensitik paslanmaz çelik AISI 431 ve düşük karbonlu çelik AISI 1020 birçok farklı endüstride birlikte kullanılan malzemelerdir. Ancak bu malzemeleri kaynak ederken (Fusion welding) önemli sorunlarla karşılaşılmaktadır. Bu nedenle, birbirine benzemeyen bu metalleri birleştirmek için sürtünme kaynağı işlemi (Solid-state welding) kullanılmaktadır. Bu malzemelerin sürtünme kaynağı ile birleştirilmesi konusunda çok az çalışma bulunmaktadır. Bu yüzden, birbirine benzemeyen bu çelik çiftlerinin sürtünme kaynağı ile birleştirilmesinde kullanılan kaynak parametrelerinin optimizasyonu büyük önem taşımaktadır. Ayrıca sürtünme kaynağı parametrelerine bağlı faktörlerin etkilerinin iyi anlaşılması gerekmektedir. Bu çalışmada, AISI 431 ve AISI 1020 çelik çubuklar sürtünme kaynağı ile başarılı bir şekilde birleştirilmiş, kaynak parametrelerinin çekme

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mukavemeti ve eksenel kısalma üzerindeki etkileri araştırılmış ve kaliteli kaynak bağlantıları elde etmek için Taguchi yöntemi kullanılarak kaynak parametreleri optimize edilmiştir. Çalışmanın deneysel sonuçları, bağlantıların en yüksek çekme dayanımının (573.32 MPa) %54.53, en düşük çekme dayanımından (370.99 MPa) daha yüksek olduğunu, en yüksek eksenel kısalmanın (23.18 mm) %650.16, en düşük eksenel kısalmadan (3,09 mm) daha yüksek olduğunu göstermiştir. Ortalama eksenel kısalma ve ortalama çekme mukavemeti için optimal parametreler A3B1C3 ve A3B3C2 olarak belirlendi; ve sırasıyla, eksenel kısalma ve çekme mukavemeti için en yüksek yüzde katkıdeğerleri %51.55 (dönme hızı) ve %63.90 (dönme hızı); ortalama eksenel kısalma ve ortalama çekme dayanımları için R^2 değerleri %97 ve %99.3 olarak bulunmuştur.

Anahtar Kelimeler*- *Sürtünme Kaynağı, Optimizasyon, Taguchi Yöntemi, AISI 431, AISI 1020

I. INTRODUCTION

Joining of metals is an important requirement in today's manufacturing industries. Therefore, the joining process should be safe, high quality and cost-effective in line with the demand of the manufacturing industry. The most commonly used method for this purpose is welding method. Welding is a widely used technique for joining dissimilar metals. However, due to different properties of the materials such as chemical, thermal and mechanical, traditional welding process (fusion welding) cannot be of the desired quality. In such cases, the friction welding process (Solid-state welding) is used to join dissimilar metals [1-5]. Friction welding method is one of the leading welding techniques that joins dissimilar metals with high quality. In friction welding method, not using materials that cause extra costs such as shielding gases, welding guns and electrodes compared to traditional welding methods present remarkable advantages. This welding method is used in many different industries such as aviation, marine and automotive. Moreover, it has many positive aspects such as easy applicability to dissimilar metals, ease processing and short processing time [4-7].

Stainless steels and low carbon steels are materials used together in many different industries (energy, aviation, automotive, etc.). These steels are used by joining with the help of friction welding methods according to the needs of the places of use. However, important problems are encountered when welding these materials to each other. One of the most important problems that arises during the welding of stainless steels and carbon steels with friction welding method is the possibility of carbide formation in the fusion zone due to high carbon ratio in carbon steels. Carbide formations in the fusion zone will increase the hardness and brittleness of the weld zone and eventually cause cracking. Therefore, in order for the welding process to be of the desired quality, the welding parameters of friction welding must be specially optimized for dissimilar steels (stainless steel and low carbon steel) [8-11].

Low carbon steel AISI 1020 is one of the widely used steel materials due to its many advantages such as low carbon content, good mechanical properties and low cost. These types of steel are found in many different industries, from automotive to aerospace [12-14]. Martensitic stainless steels are widely used materials due to their excellent properties such as high strength, good ductility, corrosion resistance and toughness. These steels are used in many different and wide industrial fields such as chemistry, medicine, automotive and aerospace. Depending on specific application fields they are used, these types of steels can be applied heat treatment to obtain different mechanical properties. This feature provides considerable flexibility to the user. One of the most remarkable of these steels is martensitic stainless steel AISI 431 [8,15,16].

AISI 431 and AISI 1020 steels are used in various industries. However, there are very few studies on joining these materials with friction welding. Therefore, the optimization of the welding parameters used in joining these dissimilar steel pairs with friction welding is of great importance. In addition, the effects of the factors depending on friction welding parameters need to be well understood.

In a study performed by Li et al. [17], they investigated the heat generation and atomic diffusion behaviour during friction welding. In their study with K61 and Ti alloy, they stated that the friction power increases with the augmentation of rotational speed or axial pressure. In addition, they exhibited that the most important factor during friction welding is the joint temperature. Ren et al. [18] concluded that hot deformation behaviours during friction welding (with martensitic stainless steel AISI 420) are affected by parameters such as degree of heat generated, loading rate and deformation rate. Kimura et al. [19], as a result of friction welding with low carbon steel and Ti-6Al-4 V titanium alloy, stated that the joining effect was the same at 30 MPa and 120 MPa pressure and reached 1076 °C at 30 MPa. Winiczenko [20] examined the effects of welding parameters on tensile strength of joints of

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dissimilar low carbon steel AISI 1020 and ductile iron ASTM A536 materials joined by friction welding. The results of the study showed that the tensile strength increased with the increase of friction force and friction time. Kimura et al. [21] investigated the effects of welding parameters on tensile strength of low carbon steel and brass joints joined by friction welding. Results showed that low friction pressure and low friction time negatively affect the tensile strength of the joints. Handa and Chawla [3] studied the effect of forging pressure on tensile strength of AISI 1021 ferritic steel and AISI 304 austenitic stainless-steel joints joined by friction welding. They stated that forging pressure has important effects on friction welding and should be chosen carefully. Udayakumar et al. [22] investigated the effects of welding parameters on tensile strength of stainless steel (UNS S32760) joints joined by friction welding. They stated that forging force and friction force are the most important parameters as a result of the optimization they performed with the response to surface methodology using welding parameters. Anitha et al. [23] examined the effects of welding parameters such as friction pressure and rotational speed on the tensile strength of martensitic stainless steel (SS410) and IN718 alloy steel joints joined by friction welding. They stated that the increase in friction pressure and rotational speed have a positive effect in increasing the tensile strength. Stalin et al. [24] studied the effects of welding parameters such as friction pressure, forging pressure and friction time on tensile strength of austenitic stainless steel (AISI 310L) joints joined by friction welding. The results showed that the most important effect among the welding parameters was provided by friction pressure. Handa and Chawla [25] examined the effect of friction pressure on tensile strength of stainless steel AISI 304 and low allow steel AISI 1021 joints joined by friction welding. They stated that increased friction pressure creates high temperatures and this causes diffusion of elements in the welding.

As a result of the literature review, it was seen that friction welding parameters such as rotational speed, forging pressure, friction time, friction pressure and forging time significantly affect the mechanical properties of the joints. Therefore, it is understood that optimizing these parameters will increase the quality of the weld.

The aim of this work is to analyse the effects of welding parameters on tensile strength and axial shortening of AISI 431 and AISI 1020 steel rod joints joined by friction welding, and to optimize the welding parameters by using Taguchi method to obtain quality weld joints.

II. MATERIAL AND METHOD

In the present work, commercial materials AISI 1020 and AISI 431 cylindrical rod pairs were used. AISI 1020 is one of the widely used steel materials due to its many advantages such as low carbon content, good mechanical properties and low cost. These types of steels are found in many different industries [12-14]. Martensitic stainless steel such as AISI 431 is a widely used material due to its excellent properties such as corrosion resistance, high strength, good ductility and toughness. These steels are used in many different and wide industrial fields such as chemistry, medicine, automotive and aerospace [8,15,16]. For this reason, these two materials were chosen to be used in the study. The welding process of these material pairs was conducted by means of a direct drive friction welding device (Fig. 1).

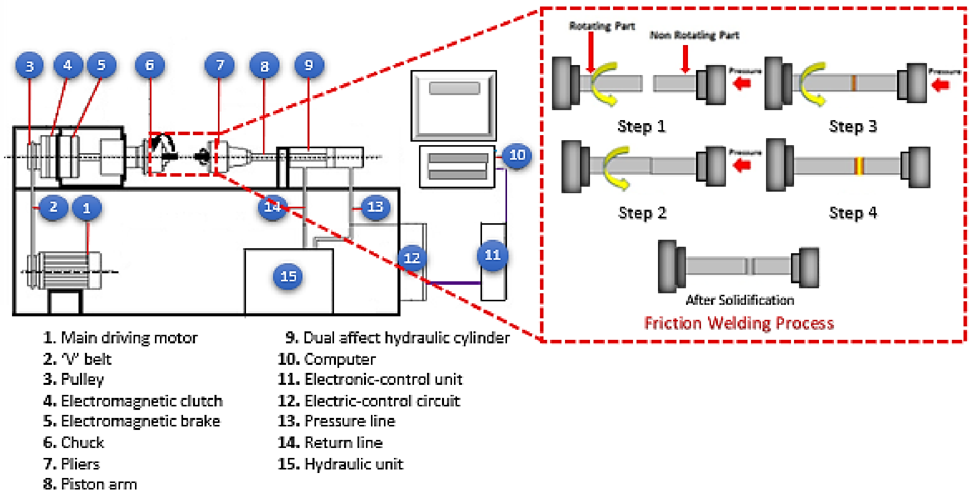

Figure 1. Friction welding device and process.

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As seen in Fig. 2 a and b, C element values (wt. %) of AISI 431 and AISI 1020 steel materials used in the study are close to each other, but there is a big difference between Si, Cr and Ni element values (wt. %).

The chemical element compositions of AISI 431 and AISI 1020 used in the work are given in Fig. 2.

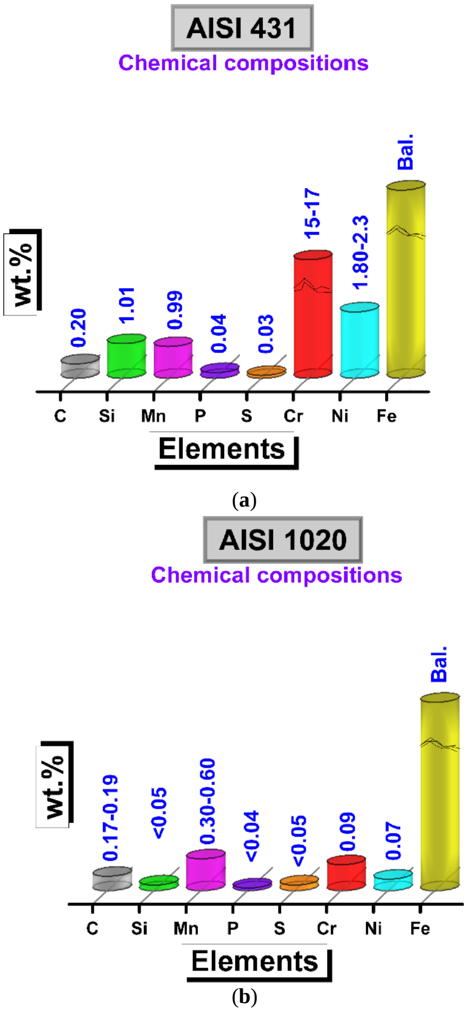

Figure 2. Chemical element compositions; AISI 431 (**a**) and AISI 1020 (**b**).

In friction welding process, optimization technique was used to obtain high quality weld joints (for optimal welding parameters) from AISI 431 and AISI 1020 steel materials.

A. Taguchi method

In line with the demands of different industrial areas, it is desired that the welding quality of the joints to be manufactured using friction welding should be high. For this reason, the tensile strength of the joints of the materials joined by friction welding should be high, thus the loss of the materials used should be minimal [1-5]. Optimization of friction welding parameters gains importance in order to achieve these targets. Nowadays, many optimization techniques are used in most of the manufacturing industries thanks to the developing technology. One of the most common and effective optimization techniques is Taguchi method. This method is used in almost all industrial fields. Taguchi optimization technique provides high quality friction weld joints with cost effective way. Thanks to Taguchi method, it is possible to reduce the number of experiments to be carried out in order to obtain high quality weld joints. This is the most important point that attracts significant attention of all industrial fields. Thus, time and cost savings are also achieved with optimization [26-32].

Taguchi optimization technique is an experimental design method based on factor, system and tolerance. During optimization, it determines the optimum parameters and uses them at different levels [26,27,31]. In the study, the experimental procedures prepared according to the optimization design were carried out stepwise.

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The stepwise experiment and optimization scheme of the presented work is given in Fig. 3.

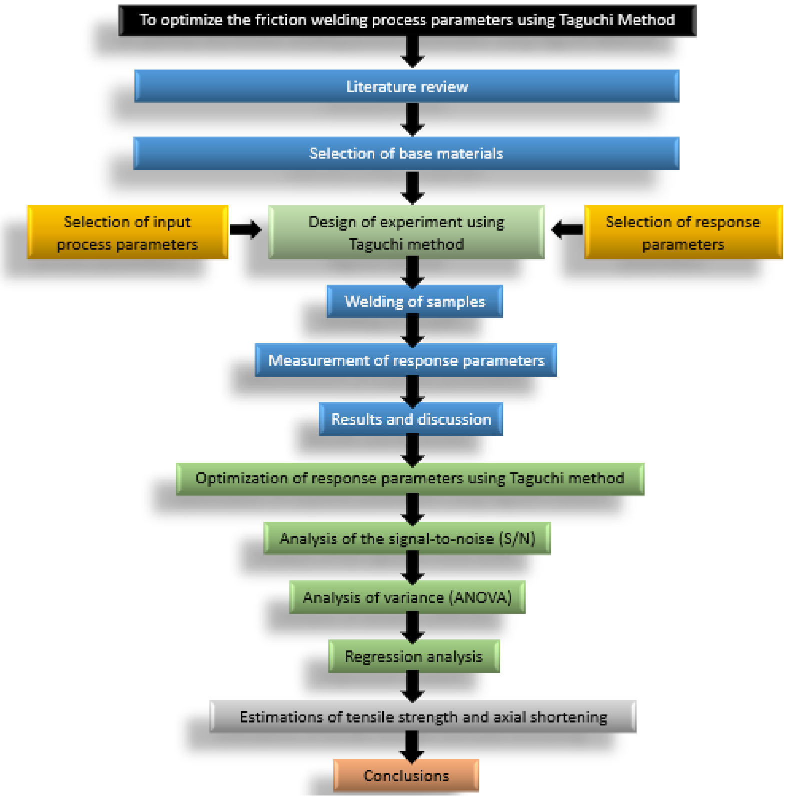

Figure 3. Stepwise experiment and optimization scheme.

Taguchi experimental design is an effective statistical method. Thanks to this statistical method, quality characteristics are examined by carrying out minimum number of experiments. Then, these experimental results are converted into Signal-to-Noise (S/N) ratios. Thus, the performance characteristics are found [26,27,31,32].

AISI 431 and AISI 1020 welded joints joined by friction welding techniquemust have high tensile strength. For this reason, in this study, "The bigger is better" formula (equation 1) was used to calculate S/N ratios. In addition, it is desired that the axial shortening of the joints joined by friction welding should be minimal in order to minimize material loss. Therefore, "The smaller is better" formula (equation 2) was used to calculate S/N ratios. The calculation formulas for tensile strength and axial shortening are presented below.

The larger is better: $S/N = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$ (1)

The smaller is better: $S/N = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$ (2)

With,

n: Number of observations,

yi: *i*-the number of observations and

S/N: Signal to noise ratio.

Within the scope of the study, rotational speed (1300, 1500 and 1700 rpm), friction time (3, 5 and 7 s), friction pressure (40, 60 and 80 MPa), forging pressure and forging time were used as welding parameters. Parameters such as forging time and forging pressure were kept constant; thus, the effects of other parameters were examined.

It was understood that the most suitable Orthogonal Array (O.A.) for the experimental study is L9. The welding parameters prepared according to Taguchi experimental design is given in Table 1. As seen in the table, the experiments were arranged according to L9 orthogonal array.

Table 1. Welding parameters (L9, O.A.).

Sample no	Rotating speed (rpm)		Friction time (s)		Friction pressure (MPa)		Forging pressure (MPa)	Forging time (s)
	Coded Value	Actual Value	Coded Value	Actual Value	Coded Value	Actual Value		
S1	1	1300	1	3	1	40	60	4
S2	1	1300	2	5	2	60	60	4
S3	1	1300	3	7	3	80	60	4
S4	2	1500	1	3	2	60	60	4
S5	2	1500	2	5	3	80	60	4
S6	2	1500	3	7	1	40	60	4
S7	3	1700	1	3	3	80	60	4
S8	3	1700	2	5	1	40	60	4
S9	3	1700	3	7	2	60	60	4

Parameters, factor symbols and levels used for optimization processes are given in Table 2.

Table 2. Parameters, factor symbols and levels.

Parameters	Factor Symbols	Units	Level 1	Level 2	Level 3
Rotating speed	A	rpm	1300	1500	1700
Friction time	B	s	3	5	7
Friction pressure	C	MPa	40	60	80

B. Preparation of welding and tensile test specimens

In the study, AISI 431 (900 mm long and 40 mm diameter) and AISI 1020 (300 mm long and 30 mm diameter) steel rod materials were prepared for friction welding experiments by turning 95 mm in length and 26 mm in diameter on Takisawa EX-108 brand Computer Numerically Controlled (CNC) lathe. The surfaces of all samples were cleaned from dirt, rust, etc. before friction welding and tensile testing.

After the friction welding processes were completed, the welded samples were machined according to ASTM E8 (Fig. 4) standards for tensile testing [33].

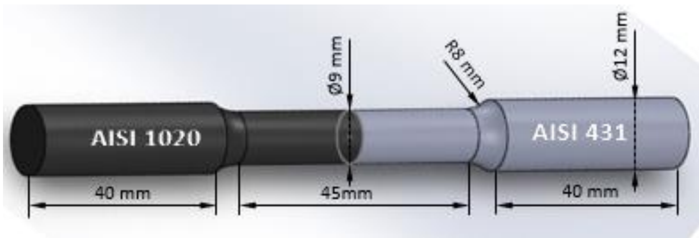

Figure 4. The sizes of tensile test sample.

Shimadzu (250 kN) brand universal tensile testing machine was used for the samples joined by friction welding. All tensile tests were performed at 1 mm x min-1 crosshead speed. The tests were carried out at ambient temperature (20±2 °C) with 50 % humidity. A picture of the machine used for the tensile tests and a sample attached during the tensile test are given in Fig. 5.

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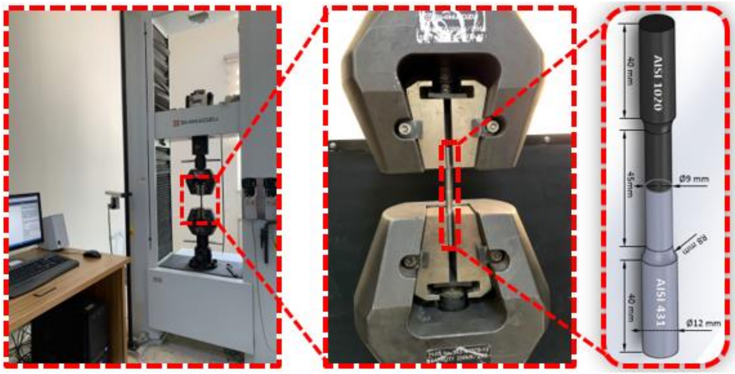

Figure 5. Tensile testing machine.

The tensile tests of all samples were performed on the same day and consecutively. The experimental methodology of the study is illustrated in Fig. 6. As seen in Fig. 6, time-dependent images of S9 sample during friction welding are shown.

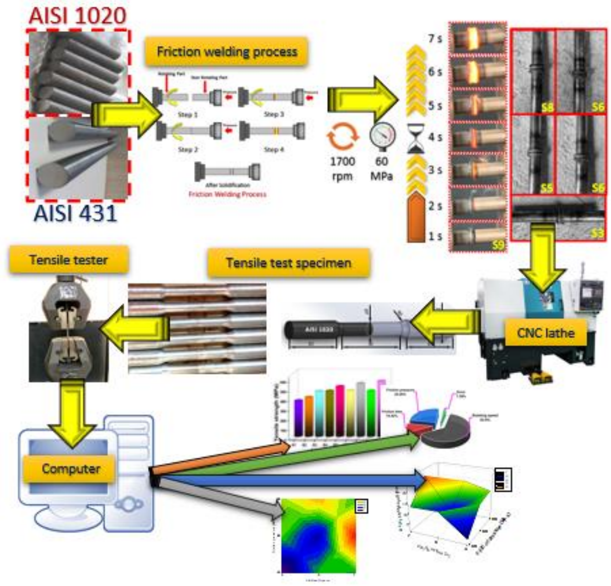

Figure 6. Experimental methodology.

III. RESULTS AND DISCUSSIONS

A. The results of tensile tests

Friction welding parameters such as rotating speed, forging pressure, friction time, friction pressure and forging time significantly affect the welding quality of joints. However, due to the limited number of test samples used in the study, forging time and forging pressure values were kept constant. For this reason, rotational speed (1300, 1500 and 1700 rpm), friction time (3, 5 and 7 s) and friction pressure (40, 60 and 80 MPa), which are among the most important friction welding parameters, were determined as variable parameters [21,23,24].

After friction welding processes, tensile tests were performed to control the welding quality of the samples prepared based on ASTM E8 standard. Thanks to these tensile tests, the tensile strengths of the welded joints were found. The tensile strength results of welded joints are one of the most important weld quality parameters. In addition, it is understood how friction welding parameters affect the welded joints.

As a result of the tensile tests of the welded joints, S1, S2 and S3 samples were fractured in the welding zone. The other samples (S4, S5, S6, S7, S8 and S9) were fractured in AISI 1020 at the side. However, S4, S6 and S8 samples were fractured in the heat-affected zone (HAZ), which is very close to the welded zone. At the end of the tensile tests, only the samples S4, S5, S6, S7, S8 and S9 showed ductile fracture.

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It was understood that the welding parameters applied to S1, S2 and S3 samples during friction welding are not suitable for joining these two materials. This is due to the lack of conditions such as required heat input, sufficient plastic deformation and diffusion during friction welding [8,34]. The tensile strengths of the joints joined by friction welding are given in Fig. 7.

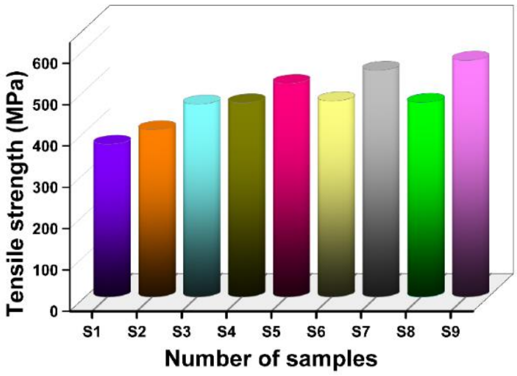

Figure 7. Tensile strength values of samples.

As a result of the tensile tests (Fig.7), the highest tensile strength value was obtained from S9 sample with 573.32 MPa, and the lowest tensile strength value was obtained from S1 sample with 370.99 MPa. For the highest tensile strength measured, while the welding parameters such as rotational speed 1700 rpm, friction time 7 s and friction pressure 60 MPa were applied for the lowest tensile strength measured, the welding parameters such as rotational speed 1300 rpm, friction time 3 s and friction pressure 40 MPa were applied. This highest measured tensile strength value is 20.69% higher than the tensile strength value of AISI 1020 steel used for friction welding. The average of all tensile strengths in the tests was found to be 478.06 MPa. The effects of friction welding parameters on tensile strength (on the left) and counter plots of friction welding parameters on tensile strength (on the right) are given in Fig. 8. The reason for this tensile strength difference is due to the high heat input, work hardening and heavy plastic deformation created in friction welding zone caused welding parameters such as applied high rotational speed, friction pressure and friction time [8,34].

In addition, the test results obtained showed that AISI 431 and AISI 1020 steel joints joined by friction welding can be improved in terms of mechanical properties.

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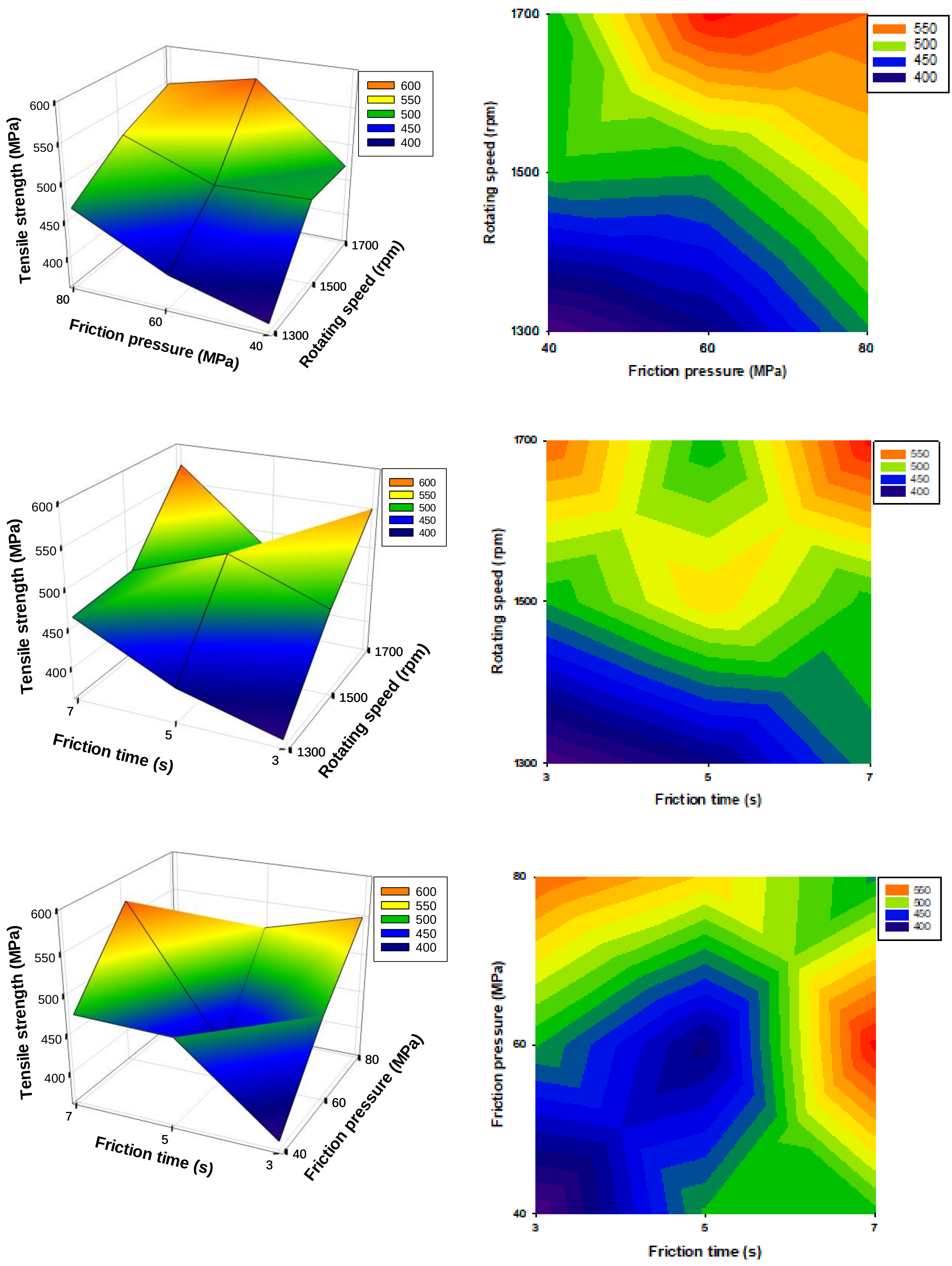

Figure 8. The effects of welding parameters on tensile strength (on the left) and counter plots of welding parameters on tensile strength (on the right).

B. The axial shortening results

The axial shortening values of AISI 431 and AISI 1020 steel joints joined by friction welding are given in Fig. 9. When the axial shortening values of the welded joints are examined, it is observed that the axial shortening values are generally negatively affected by the increase in the welding parameters.

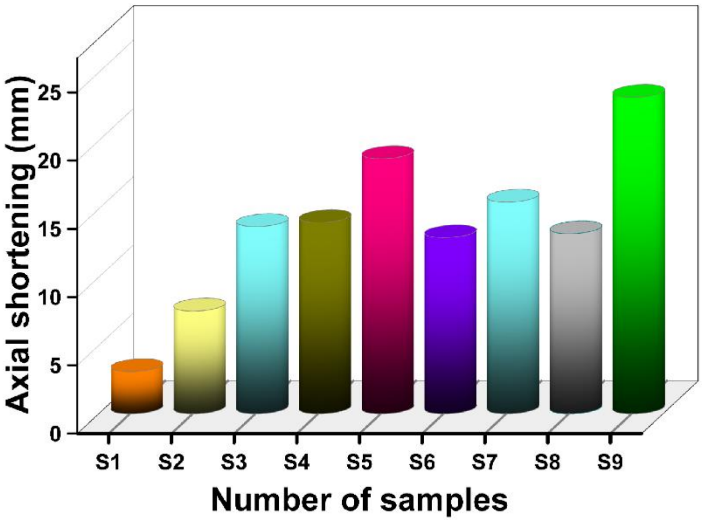

Figure 9. Axial shortening values of samples.

As a result of the friction welding, the highest axial shortening value was obtained from S9 sample with 23.18 mm, and the lowest axial shortening value was obtained from S1 sample with 3.09 mm. For the highest measured axial shortening, rotational speed 1700 rpm, friction time 7 s and friction pressure 60 MPa welding parameters, while for the lowest axial shortening measured, rotational speed 1300 rpm, friction time 3 s and friction pressure 40 MPa welding parameters were applied. This axial shortening measured as the highest value is 650.16% higher than the lowest measured axial shortening value. The average of all axial shortenings in the friction welded joints was found to be 13.54 mm. The effects of welding parameters on axial shortening (on the left) and counter plots of friction welding parameters on axial shortening (on the right) are given in Fig. 10.

In the study, it is desired that the axial shortening of the joints joined by friction welding should be minimal in order to minimize material loss. However, when the axial shortening values of the joints obtained after friction welding were examined, it was seen that the tensile strength of the joints with the least axial shortening was not good, and that the tensile test fracture occurred in the weld zone. As a result of the tensile test of welded joints, it is one of the least desirable situations for the fracture site to be in the welded zone [1, 2, 4]. Therefore, when the axial shortening and tensile test results were evaluated together, it was seen that the sample with the most suitable welding parameters was S7.

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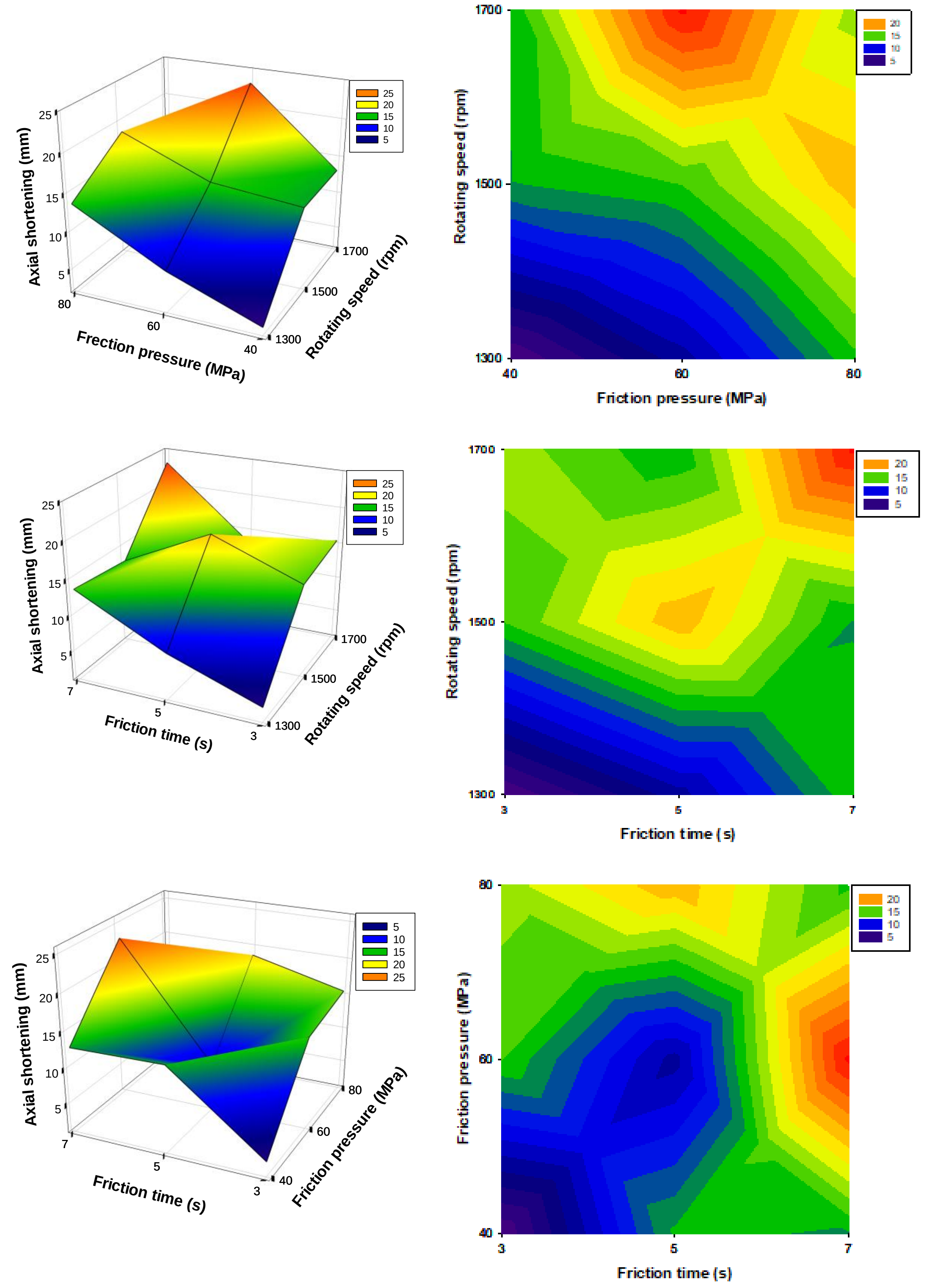

Figure 10. The effects of welding parameters on axial shortening **(**on the left**)** and counter plots of welding parameters on axial shortening **(**on the right**)**.

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C. Analysis of S/N ratios

S/N ratios were found after the experiments performed according to Taguchi experimental design. S/N ratios were calculated for tensile strength and axial shortening using equation 1 (The larger is better) and equation 2 (The smaller is better), respectively. Thanks to these calculated S/N ratios, the control factors were optimized [26, 27, 35]. S/N response table and factor rankings for tensile strength and axial shortening are given in Table 3.

Table 3. S/N response table and factor rankings for tensile strength and axial shortening.

Tensile strength

Response Table for Signal to Noise Ratios
Larger is better

Level	Rotating speed (rpm)	Friction time (s)	Friction pressure (MPa)
1	52.30	53.20	52.79
2	53.75	53.29	53.58
3	54.47	54.03	54.15
Delta	2.17	0.83	1.36
Rank	1	3	2

Response Table for Means
Larger is better

Level	Rotating speed (rpm)	Friction time (s)	Friction pressure (MPa)
1	414.0	463.0	438.7
2	487.3	464.3	482.7
3	531.0	505.0	511.0
Delta	117.0	42.0	72.3
Rank	1	3	2

Axial shortening

Response Table for Signal to Noise Ratios
Smaller is better

Level	Rotating speed (rpm)	Friction time (s)	Friction pressure (MPa)
1	-16.69	-18.85	-18.14
2	-23.52	-21.79	-22.59
3	-24.51	-24.09	-24.00
Delta	7.81	5.24	5.86
Rank	1	3	2

Response Table for Means
Smaller is better

Level	Rotating speed (rpm)	Friction time (s)	Friction pressure (MPa)
1	8.113	10.870	9.727
2	15.200	13.137	14.907
3	17.293	16.600	15.973
Delta	9.180	5.730	6.247
Rank	1	3	2

Main effect plots for S/N ratios of axial shortening and tensile strength are shown in Fig. 11 and 12. In the main effects plot for S/N ratios, the values closest to the vertical are the optimal level factor. The optimal level factor found is defined as the most effective parameter. As seen in Table 3 and Fig. 11, the most important parameter for the axial shortening is the rotating speed. The most suitable parameters (based on S/N ratios) for the average axial shortening were determined as A3B1C3. As can be seen in Table 3 and Fig. 12, the most important parameter for the tensile strength is the rotating speed. The most suitable parameters (based on S/N ratios) for the average tensile strength were determined as A3B3C2.

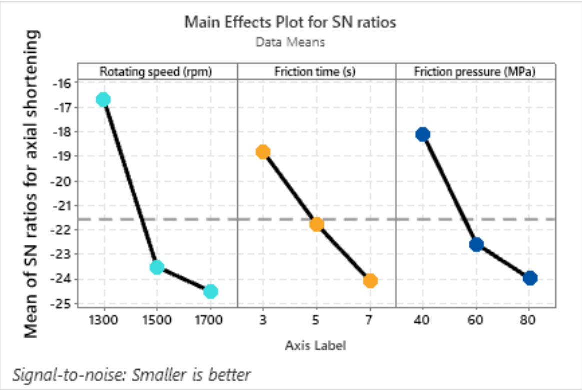

Figure 11. Main effects plot for S/N ratios of axial shortening.

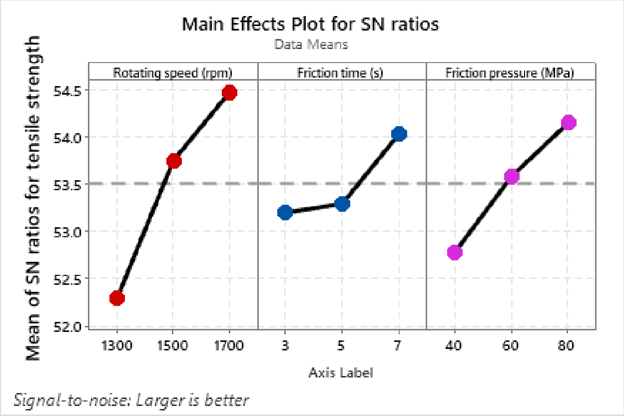

Figure 12. Main effects plot for S/N ratios of tensile strength.

D. Analysis of ANOVA results

In the study, ANOVA (Analysis of Variance) analysis (statistical method) was performed to see the effects of the factors. For this, the results obtained from the experiments were used in ANOVA analysis. These analyses were performed for tensile strength and axial shortening at 95% confidence and 5% significance levels [26,27,35]. The results of ANOVA analyses for tensile strength and axial shortening are given in Table 4.

Table 4. The ANOVA results.

			Tensile strength				
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Rotating speed (rpm)	2	20973.6	63.90%	20973.6	10486.8	45.97	0.021
Friction time (s)	2	3419.6	10.42%	3419.6	1709.8	7.50	0.118
Friction pressure (MPa)	2	7970.9	24.29%	7970.9	3985.4	17.47	0.049
Error	2	456.2	1.39%	456.2	228.1		
Total	8	32820.2	100.00%				
R-sq: 98.61%		R-sq(adj): 94.44%					

			Axial shortening				
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Rotating speed (rpm)	2	138.88	51.55%	138.88	69.438	10.20	0.045
Friction time (s)	2	49.97	18.54%	49.97	24.983	3.67	0.114
Friction pressure (MPa)	2	66.99	24.86%	66.99	33.496	4.92	0.069
Error	2	13.61	5.05%	13.61	6.805		
Total	8	269.44	100.00%				
R-sq: 94.95%		R-sq(adj): 79.80%					

Notes: Adj. SS, Adjusted Sum of Squares; Seq. SS, Sequential Sum of Squares; Adj. MS, Adjusted Mean Squares; P, Statistical value; F, Statistical test.

As seen in Table 4 and Fig. 13 a, when the percentage contribution values for tensile strength are examined, it is seen that the most effective factor is rotating speed (63.90%). In addition, the contribution values (tensile strength) for friction pressure and friction time are 24.29% and 10.42%, respectively. As can be seen in Table 4 and Fig. 13 b, the most effective factor for axial shortening is the rotating speed with 51.55%. Also, the contribution values (axial shortening) for friction pressure and friction time are 24.86% and 18.54%, respectively. When the percent contribution values of tensile strength and axial shortening are evaluated together, it is seen that the most important factor is the rotational speed.

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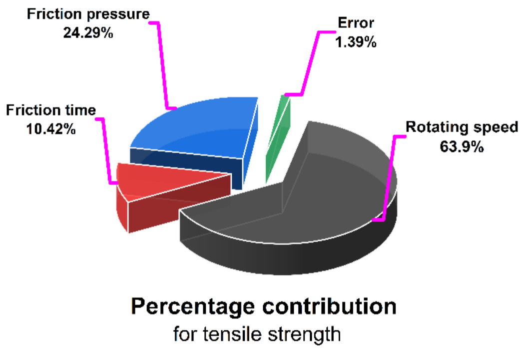
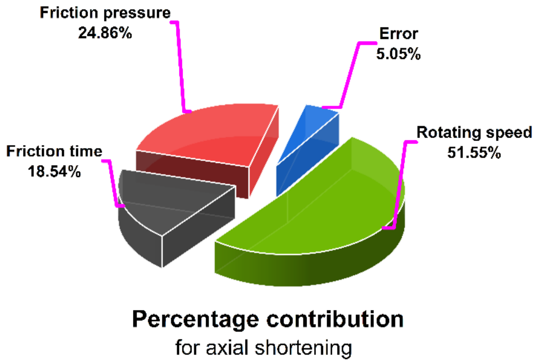


(a)



(b)

Figure 13. Percentage contributions; tensile strength **(a)** and axial shortening **(b)**.

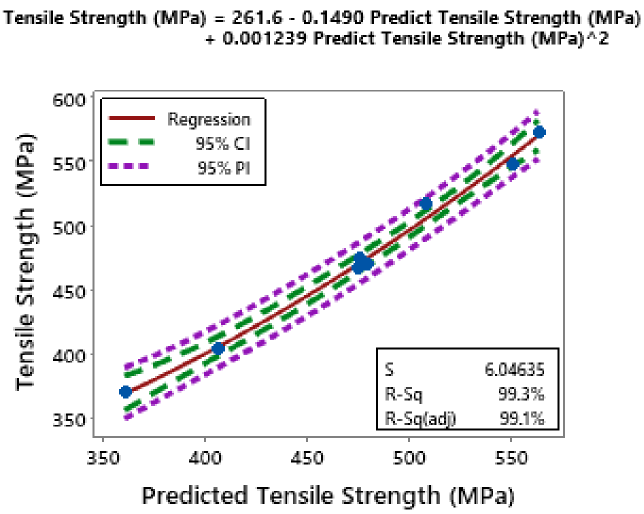
E. Analysis of regression

Regression analyses are carried out to analyse and model different variables that have a relationship between the dependent variable and the independent variables (one or more) [26, 27, 35-42]. In this study, equations were found by regression analysis for the estimation of axial shortening and tensile strength. Linear models were made to find the equation estimates. The equations found for tensile strength and axial shortening as a result of the regression analysis are given in Table 5.

Table 5. Linear equations.

Estimated linear equations
Tensile Strength (MPa) = 477.44 - 63.44 Rotating speed (rpm)_1300 + 9.89 Rotating speed (rpm)_1500 + 53.56 Rotating speed (rpm)_1700 - 14.44 Friction time (s)_3 - 13.11 Friction time (s)_5 + 27.56 Friction time (s)_7 - 38.78 Friction pressure (MPa)_40 + 5.22 Friction pressure (MPa)_60 + 33.56 Friction pressure (MPa)_80
Axial shortening (mm) = 13.536 - 5.42 Rotating speed (rpm)_1300 + 1.66 Rotating speed (rpm)_1500 + 3.76 Rotating speed (rpm)_1700 - 2.67 Friction time (s)_3 - 0.40 Friction time (s)_5 + 3.06 Friction time (s)_7 - 3.81 Friction pressure (MPa)_40 + 1.37 Friction pressure (MPa)_60 + 2.44 Friction pressure (MPa)_80

The comparison of the experimental results (tensile strength and axial shortening) with the estimated values (tensile strength and axial shortening) are given in Fig. 14 a and b (for output parameters).



(a)

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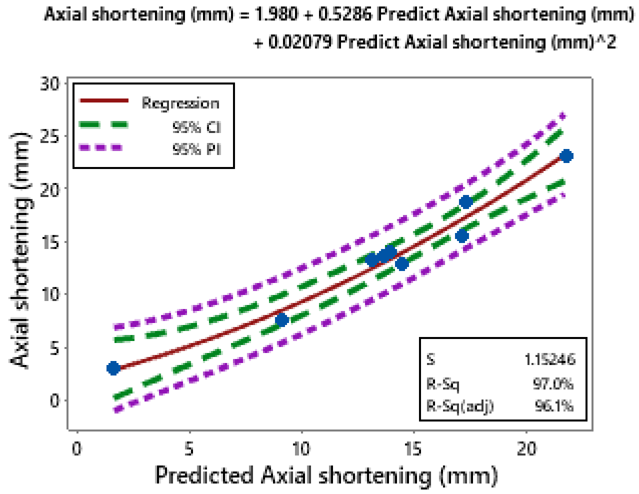
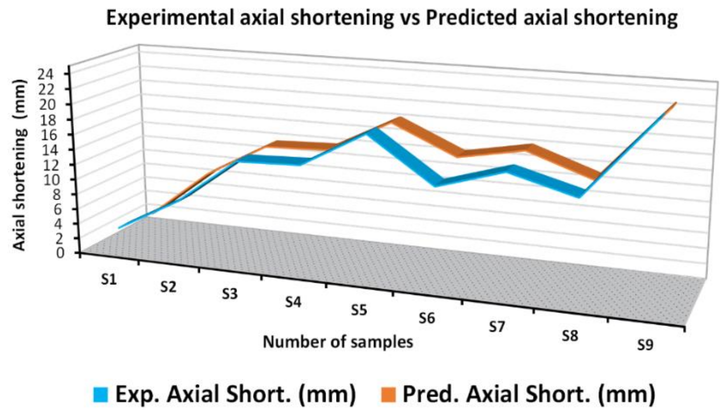


(**b**)

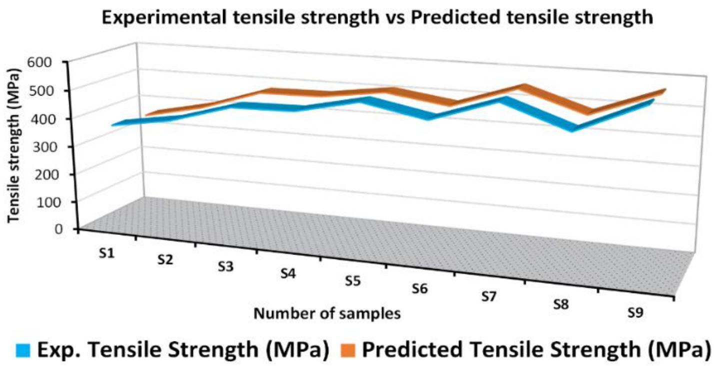
Figure 14. Experimental results vs predicted values; tensile strength **(a)** and axial shortening **(b)**.

As seen in Fig. 14 a and b, a good correlation was found when the predicted values with the experimental results were examined. R2 values for the average axial shortening and average tensile strengths were found to be 97% and 99.3%, respectively.

The graphs in Fig. 15 a and b show the experimental results versus the predicted values for axial shortening and tensile strength.



(**a**)



(**b**)

Figure 15. Experimental vs predicted values; axial shortening **(a)** and tensile strength **(b)**.

IV. CONCLUSIONS

In the present study, AISI 431 and AISI 1020 steel bars were successfully joined by friction welding, and the effects of welding parameters on axial shortening and tensile strength were investigated, and welding parameters were optimized using Taguchi method to obtain quality weld joints. Within the scope of the study, rotational speed (1300, 1500 and 1700 rpm), friction time (3, 5 and 7 s), friction pressure (40, 60 and 80 MPa), forging pressure and forging time were used as welding parameters. The results of the study are summarized below:

- At the end of the tensile tests of the welded joints, S1, S2 and S3 samples were fractured in the welding zone. The other samples (S4, S5, S6, S7, S8 and S9) were fractured in AISI 1020 at the side. In addition, only S4, S5, S6, S7, S8 and S9 samples showed ductile fracture.
- In the tests, the highest tensile strength value was obtained from S9 sample with 573.32 MPa, and the lowest tensile strength value was obtained from S1 sample with 370.99 MPa. Thus, it was observed that the highest tensile strength was 54.53% higher than the lowest tensile strength. Furthermore, the highest measured tensile strength value was 20.69%, higher than the tensile strength value of AISI 1020 steel used for friction welding.
- At the end of friction welds, the highest axial shortening value was obtained from S9 sample with 23.18 mm, and the lowest axial shortening value was obtained from S1 sample with 3.09 mm. This highest measured axial shortening value was 650.16% higher than the lowest measured axial shortening value.
- The optimal parameters (according to S/N ratios) for average axial shortening and average tensile strength were determined as A3B1C3 and A3B3C2, respectively.
- According to ANOVA analyses, the highest percentage contribution values for axial shortening and tensile strength were found to be 51.55% (rotating speed) and 63.90% (rotating speed), respectively. Thus, it was found that the most important factor for axial shortening and tensile strength is rotating speed.
- In the regression analyses, a good correlation was found. R^2 values for the average axial shortening and average tensile strengths were found to be 97% and 99.3%, respectively.

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