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Optimization of process parameters of medium carbon steel joints joined by MIG welding using Taguchi method

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Abstract: In this study, related to getting better obtain to the mechanical properties of medium carbon steel joints joined by MIG welding method using the Taguchi method welding groove were optimized. Grove angle (60º, 75º and 90º), current (100 A, 110 A and 120 A) and voltage (25 V, 30 V and 35 V) were used as welding parameters. The results showed that the highest tensile strength as 597.963 MPa was obtained at groove angle 90º, current 120 A and voltage 30 V, the lowest tensile strength was obtained as 395.125 MPa. The highest elongation as 11.551% was obtained at groove angle 90º, current 120 A and voltage 30 V, the lowest elongation was obtained as 8.354%. In addition, it was observed that the changes in current and voltage values significantly affect the tensile strength and elongation values of the joints. According to ANOVA analyses, the most effective parameter on average tensile strength and elongation were determined to be groove angle (62.75% and 75.58%, respectively). Based on S/N ratios, the optimal parameters for average tensile strength and elongation were determined A3B3C2 factors.

Keywords: Optimization, Taguchi method, ANOVA, MIG welding, AISI 1040, Tensile test

1. Introduction

In today's manufacturing industry, the need for high-strength and cost-effective metal joining is increasing day by day. In accordance with these growing needs and demands purposes, one of the leading methods is welding. Welding is the most common method used to obtain high-strength, reliable and low-cost metal joints [1-3]. Gas Metal Arc Welding (GMAW/MIG) is one of the most preferred methods of joining metals by welding. This welding method has many advantages such as optimum product cost, better surface quality, strength and reasonable production speed [4-6]. The Metal Inert Gas (MIG) welding process is known as GMAW. In this process, the heat of the electric arc is used to melt metallic components and the consumable electrode wire. During the process, the filler wire is continuously fed into the weld pool by the welding gun and thus the main materials are joined. Gas shielding (argon, carbon dioxide or various other gas mixtures) atmosphere is created around the welding zone to protect the weld deposit from contaminants [5-8].

Medium carbon steels such as AISI 1040 are used extensively in different industries due to their properties such as strength, wear resistance and high toughness. Therefore, they are used in a variety of industrial applications including crankshafts, light gears, worms, axles, bolts, connection rods, spindles and many other automotive, aerospace, petroleum and piping products [9, 10]. Manufacturing complex parts using AISI 1040 steels without joints as a single component is a cumbersome task. Therefore, they are joined by welding [11].

The strength of the joints to be made by MIG welding method of this steel material is requested to be the highest. In accordance with this purpose, remarkable studies in the literature on joints made with MIG welding method were examined.

Amit Pal [12] investigated the effects of different welding parameters such as welding current (A), voltage (V) and filler wire rate on the tensile strength of medium carbon steel joints joined by MIG welding. In the study, Taguchi method is used to optimize the effects of parameters on weld quality. As a result of his study, he reported that the quality of the joints is affected by different welding factors such as welding voltage, current, filler wire rate and affects the results produced from the tensile test [12]. Utkarsh et al. [13] examined the highest tensile strength of St-37 steel joints joined by MIG welding. In the study, Taguchi Orthogonal array is used to optimize

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Table 1. Chemical compositions.

Material	Elements of composition (wt. %)								
	C	Si	Mn	P, S	Cr	Mo	Ni	Cu	Fe
AISI 1040	0.37-0.44	0.10-0.40	0.50-0.80	≤0.045	0.03	0.009	0.04	0.06	Balanced

the effects of parameters on weld quality. Gas flow rate, current (I), Voltage (V), and welding speed parameters were used for the study. As a result of their studies, they stated that current and voltage have significant effects on tensile strength [13]. In a study performed by Narwadkar and Bhosle [14], the optimization of parameters such as gas flow rate, voltage and current in Fe410WA type steel joints joined by MIG welding was investigated using the Taguchi method. As a result of their study, they stated that gas flow rate, current and voltage have important effects on joints [14]. Sankar et al. [15] studied the effects of welding parameters such as welding voltage, current and gas flow rate on weld joints of AISI 310 steel joints joined by MIG welding. In the study, the Taguchi method was used to optimize the effects of the parameters. The results of their study showed that the welding current has significant effects on the welding process [15]. Kumar and Roy [16] examined the effects of different welding parameters such as welding voltage (V), current (A), filler wire rate on AISI 304 and low carbon steel joints joined by MIG welding. In the study, Taguchi method is used to optimize the effects of parameters on weld quality. As a result of their study, they reported that the quality of the joints is affected by many factors such as welding voltage, filler wire rate and current [16]. Moghaddam et al. [17] investigated the MIG process to optimize the weld seam geometry and heat affected zone of SA387 steel plates. In the study, the Taguchi method was used to optimize the effects of parameters on the weld quality. As a result of their studies, they stated that welding current, voltage and bevel angle have significant effects on welding quality [17]. In a study performed by Arya et al. [18], they stated that the highest tensile strength was achieved by using the Taguchi method in alloy steel joints joined by MIG welding. As a result of their review, they reported that welding speed is the most vital factor for tensile strength [18]. Patil and Waghmare [19] investigated on increasing the tensile strength of AISI 1030 steel joints joined by MIG welding. In the study, the Taguchi method was used to optimize the effects of parameters on the weld quality. As a result, they reported that the welding speed has a significant effect on the tensile strength [19]. Mishra et al. [20] studied the effects of welding parameters such as welding voltage, welding speed and welding current on penetration depth of AISI 1020 steel joints joined by MIG welding. In the study, the Taguchi method was used to optimize the effects of parameters on the weld quality. They reported that the optimum penetration depth was obtained [20].

The literature review revealed that many welding parameters such as voltage, current, gas flow rate, filler wire used for MIG welding significantly affect the mechanical properties. Therefore, it is necessary to optimize these parameters. In addition, it has proven that mechanically desired results are obtained when the welding parameters are optimized with the Taguchi method.

In this study, it was aimed to analyse the mechanical properties of AISI 1040 steel rod joints joined by MIG welding, and to optimize the input parameters with the help of Taguchi method to obtain good mechanical properties.

2. Material and Method

2.1. Material, filler wire and welding parameters

In this study, commercial material medium carbon steel AISI 1040 cylindrical rods were used. AISI 1040 steels have attracted attention due to their properties such as high strength, wear resistance, and toughness. Because of these properties, light gears, crankshafts, axles, worms, connecting rods, bolts, spindles, torsion bars and many other It is used in a variety of industrial applications including aerospace, automotive, petroleum and piping products [9, 10]. The chemical compositions and mechanical properties of AISI 1040 used in the study are given in Table 1 and Table 2.

Table 2. Mechanical properties.

Material	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
AISI 1040	666	358	22.7

In the study, ER70S-6 (AWS A5.18) filler wire was used for MIG welding. ER70S-6 filler wires are used with pure CO_2 or a mixture of Ar and CO_2 gases. It is a type of copper-coated steel welding. It provides higher strength and excellent welding properties [21]. It is widely used for welding metals [21-24]. These electrodes contain the highest combinations of deoxidizers in the form of manganese and silicon [24]. The diameter of filler wire used in MIG welding is 1.2 mm. The chemical compositions and mechanical properties of ER70S-6 filler wire are given in Table 3, Table 4, respectively [22].

The parameters of the welding process are given in Table 5. In accordance with ASME Specifications (AWS A5.18), a mixture of Ar (95 %) and CO_2 (5 %) was used as shielding gas to obtain quality welding [22]. All welding processes were performed at room temperature and 50±5 % relative humidity. MIG welding was performed with Arctech Arc-450 welding machine. Before the welding

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Table 3. Chemical compositions of filler wire [22].

Filler wire	Elements of composition (wt. %)								
	C	Si	Mn	P	S	Mo, Ni, Cr	V	Cu	Fe
ER70S-6	0.06-0.15	0.80-1.15	1.40-1.85	≤0.025	≤0.035	≤0.15	≤0.03	≤0.5	Balanc.

Table 4. Mechanical properties of filler wire [22].

Filler wire	(Minimum) Tensile strength (MPa)	(Minimum) Yield strength (MPa)	(Minimum) Elongation (%)
ER70S-6	480	400	22

Table 5. Welding parameters.

Sample No	Groove angle (α°)	Welding technology	Welding parameters			
			Current (A)	Voltage (V)	Welding Speed (mmxmin^{-1})	Gas flow rate (kgxhr^{-1})
S1	60°	MIG (GMAW)	100	25	30	28
S2	60°	MIG (GMAW)	110	30	30	28
S3	60°	MIG (GMAW)	120	35	30	28
S4	75°	MIG (GMAW)	100	30	30	28
S5	75°	MIG (GMAW)	110	35	30	28
S6	75°	MIG (GMAW)	120	25	30	28
S7	90°	MIG (GMAW)	100	35	30	28
S8	90°	MIG (GMAW)	110	25	30	28
S9	90°	MIG (GMAW)	120	30	30	28

process, the rods were carefully cleaned of external factors such as dirt and oil that could affect a quality weld [25].

AISI 1040 steel rods, 250 mm long and 20 mm diameter, were machined on a Computer Numerically Controlled (CNC) lathe to obtain the required shape and dimensions. All samples were prepared according to ASTM E8M standard [26]. The dimensions of the samples prepared for welding are given in Fig. 1.

In MIG welding processes, welding speed and gas flow rate were kept constant in order to clearly measure the differences in mechanical properties between the joints. The experimental methodology up to the preparation of the tensile samples is given in Fig. 2. For welding process, the surfaces of the samples were cleaned with a grinding machine for make ready the tensile test.

2.2. Tensile testing

The samples prepared according to the ASTM E8M standard were carefully cleaned again from external factors such as dirt, oil and rust before the tensile test.

Tensile tests were performed with a 250 kN Shimadzu universal tester at room temperature, 50±5 % humidity and 1 mm × min^{-1} crosshead speed [27]. The tensile testing machine used in the experimental study is shown in Fig. 3.

2.3. Taguchi method

In the manufacturing industry, thanks to the advancing technology, optimization techniques have been developed to determine the effect values of the factors used during

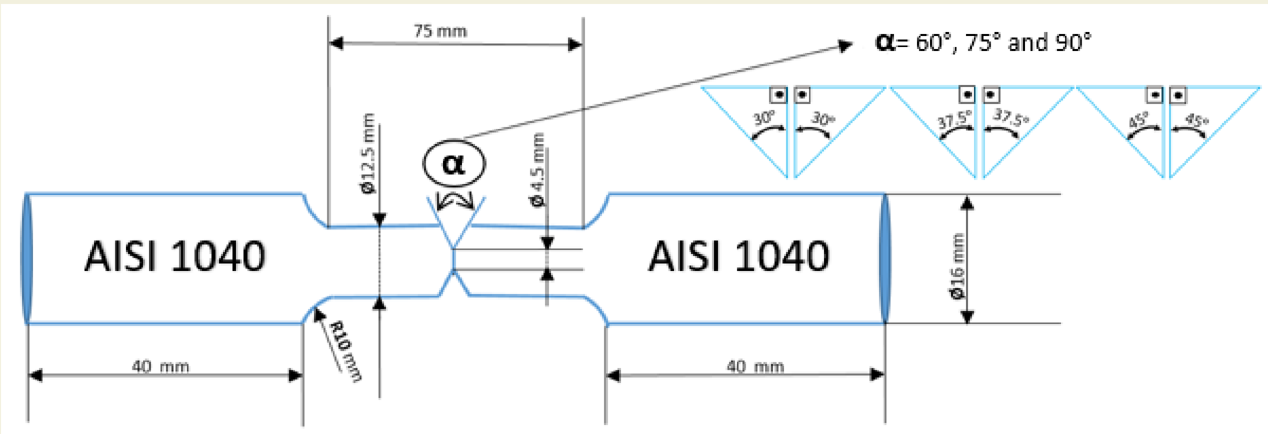

Figure 1. The dimensions of tensile test sample.

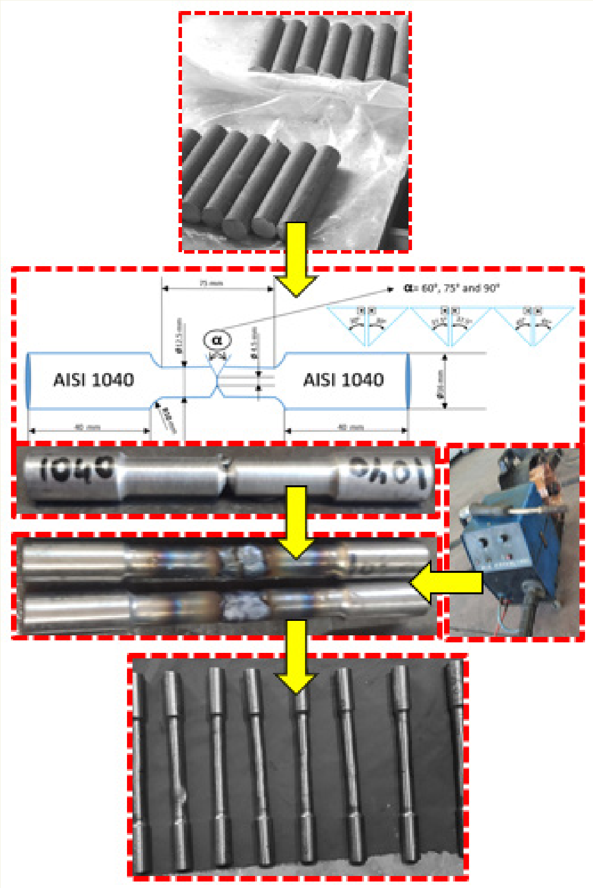

Figure 2. Experimental methodology.

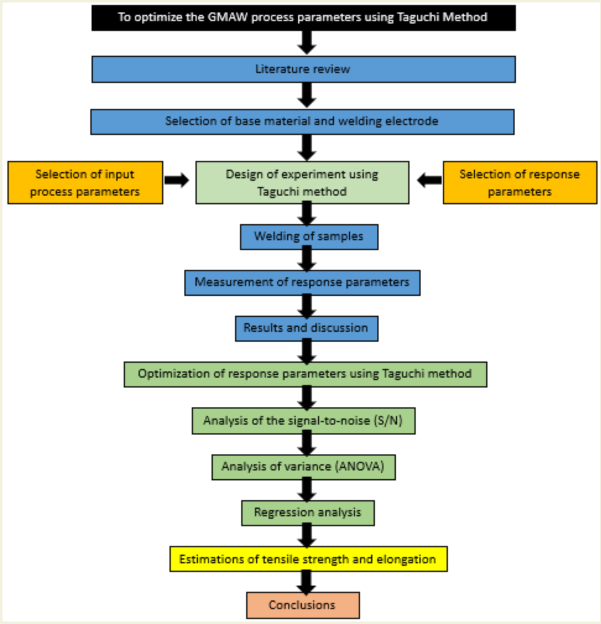

Figure 4. Stepwise experimental scheme.

product processing in order to determine the basic optimum parameters. The most prominent of these is the Taguchi optimization method. The Taguchi method is an optimization method and experimental design based on factor design, tolerance design and system design. In addition, it is used to determine the optimal parameters from different levels [4, 9, 28-32]. In the manufacturing industry, the time required for the product can be reduced by using the Taguchi method, thus reducing the costs and increasing the profit rate of the business. In addition, thanks to the Taguchi method, it is possible to control for variables that cannot be explained in the conventional experimental design. In the Taguchi method, objective function values are converted into a signal-to-noise (S/N) ratio to measure the performance characteristics of control factor levels against these factors. The S/N ratio is defined as the ratio of the desired signal to the undesired random noise value. In this way, it is used as an indicator for the quality characteristics of the experimental data [28, 31]. In the test design, each combination of control factors for tensile strength and elongation were measured. The S/N ratios were used to optimize control factors. For the calculation of S/N ratios, depending on the characteristic type, the objective functions are given as "Larger is better". Here, the "Larger is better" function (see equation (1)) is used

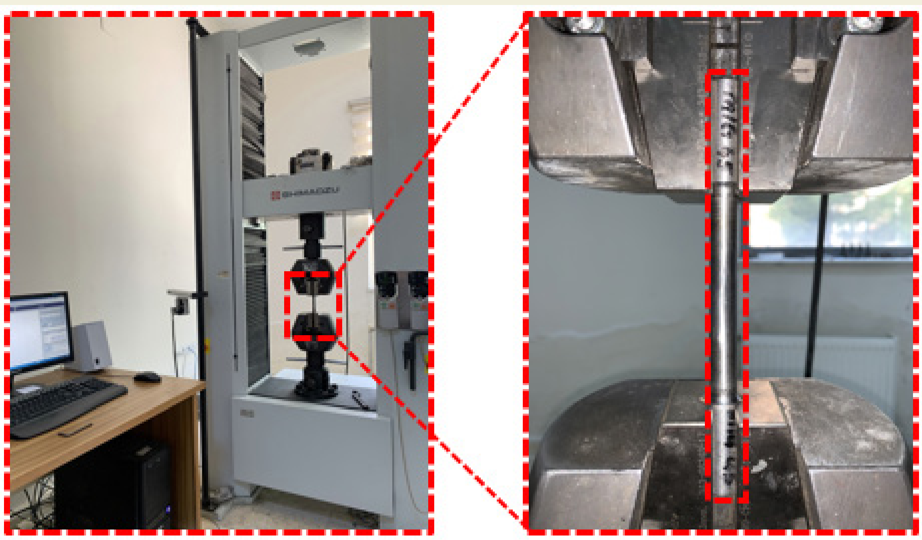

Figure 3. Tensile testing machine.

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because the tensile strength and elongation are intended to be higher.

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

with $\boldsymbol{n}$: Number of observations, $\boldsymbol{y_i}$: $\boldsymbol{i}$-th number of observations and $\boldsymbol{S/N}$: Signal to noise ratio.

Stepwise experimental scheme of the present study is shown Fig.4.

2.4. Parameters and levels

The parameters and levels used in the experimental study are given in Table 6.

Table 6. Experiment parameters and levels.

Parameters	Symbols	Units	Level 1	Level 2	Level 3
Groove angle	A	α°	60°	75°	90°
Current	B	Ampere (A)	100	110	120
Voltage	C	Voltage (V)	25	30	35

The most suitable Taguchi orthogonal experiment design (L9) for this study was chosen based on these levels (Table 7).

Table 7. Taguchi orthogonal array design L9.

Exp. no	Factor A	Factor B	Factor C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3. Results and discussion

3.1. Tensile test results

As can be seen in Table 8, Fig. 5 and Fig. 6, when the tensile test results of the joints joined by MIG welding are examined, the highest tensile strength as 597.963 MPa was obtained at groove angle 90°, current 120 A and voltage 30 V. In the tests, the lowest tensile strength was measured as 395.125 MPa. The results showed that the highest tensile strength was 51.33% higher than the lowest tensile strength value. In addition, the average tensile strength of joints welded by MIG welding was measured as 504.042 MPa. The Load- extension curves of joints joined by MIG welding are given in Fig. 5.

Table 8 and Fig.6 show the effects of the groove angles of the joints on the tensile strength values. As can be seen in the Table 8, it has been observed that the tensile strength

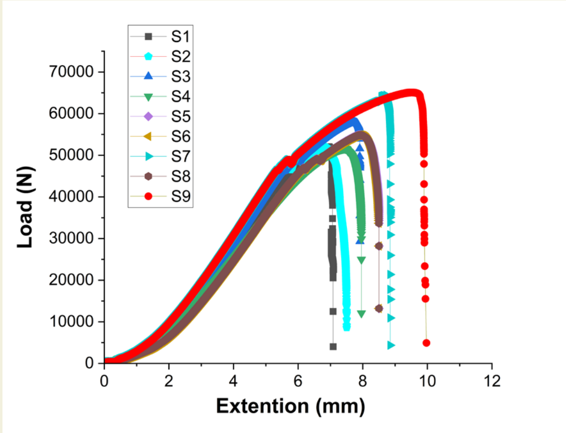

Figure 5. Load vs extension curves of samples.

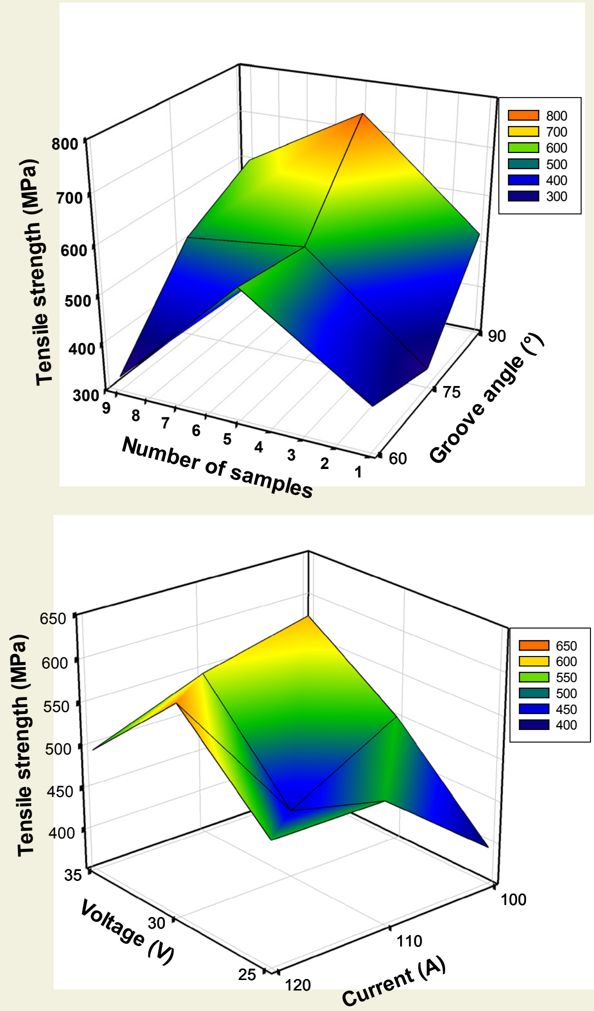

Figure 6. The Effect of welding parameters on tensile strength.

values tend to increase depending on the increase in the trough angles. In the tensile tests of the joints, the tensile strength value of the 90° groove angled S9 sample was 20.73% higher than the tensile strength value of the 60° groove angled S3 sample.

As can be seen in Table 8 and Fig. 7, when the tensile test results of the joints joined by MIG welding are examined, the highest elongation as 11.551% was obtained at

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Table 8. Experimental results as per Taguchi L9 O.A.

Sample No	Groove angle (α°)	Welding technology	Current (A)	Voltage (V)	Tensile Strength (MPa)	Elongation (%)
S1	60°	MIG (GMAW)	100	25	395.125	8.354
S2	60°	MIG (GMAW)	110	30	431.199	8.752
S3	60°	MIG (GMAW)	120	35	495.287	9.221
S4	75°	MIG (GMAW)	100	30	501.234	9.031
S5	75°	MIG (GMAW)	110	35	545.299	10.011
S6	75°	MIG (GMAW)	120	25	497.325	9.495
S7	90°	MIG (GMAW)	100	35	576.997	10.949
S8	90°	MIG (GMAW)	110	25	495.945	9.989
S9	90°	MIG (GMAW)	120	30	597.963	11.551

groove angle 90°, current 120 A and voltage 30 V. In the tests, the lowest elongation was measured as 8.354%. The results showed that the highest elongation was 38.30% higher than the lowest elongation value. In addition, the average elongation of joints welded by MIG welding was measured as 9.706%.

As seen in Table 8, it has been observed that the tensile strength and elongation values are generally positively affected by the welding parameters current and voltage increase. In addition, it has been seen that the increases in the tensile strength value due to increasing current and voltage are compatible with previous studies in the literature [12, 13, 20, 33].

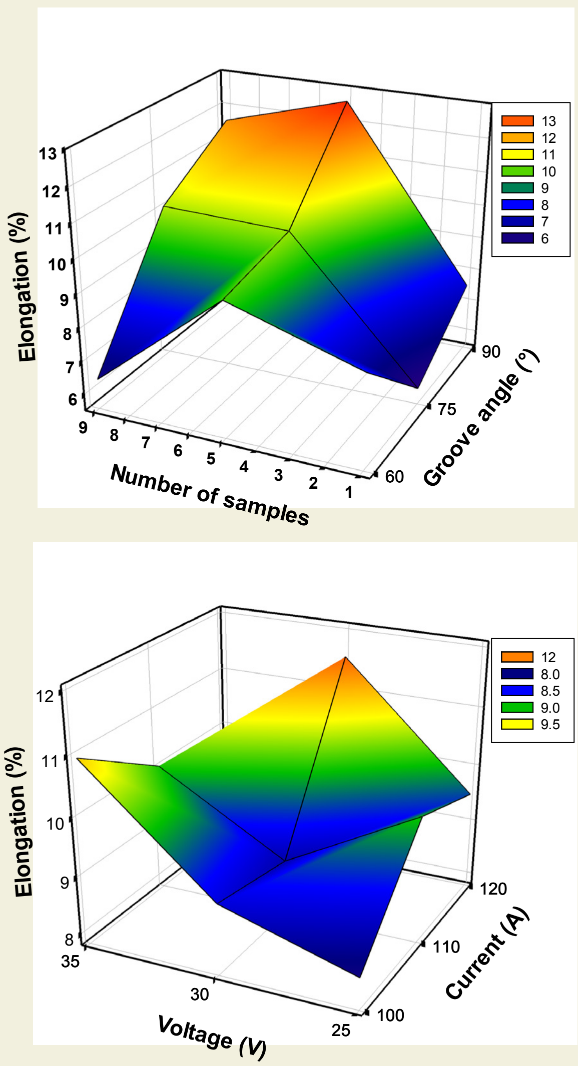


Figure 7. The Effect of welding parameters on elongation.

3.2. Analysis of Signal-to-noise (S/N) ratio

Experimental design was performed using the Taguchi method in tensile tests. S/N ratios were used to optimize control factors [4, 28, 31]. The S/N ratios of the data obtained for tensile strength and elongation are given in Table 9.

As can be seen in Fig. 8 and Fig. 9, the effects of control

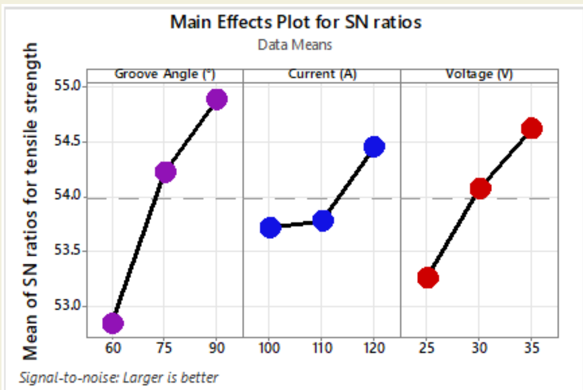


Figure 8. Main effects plot for S/N ratios (for tensile strength).

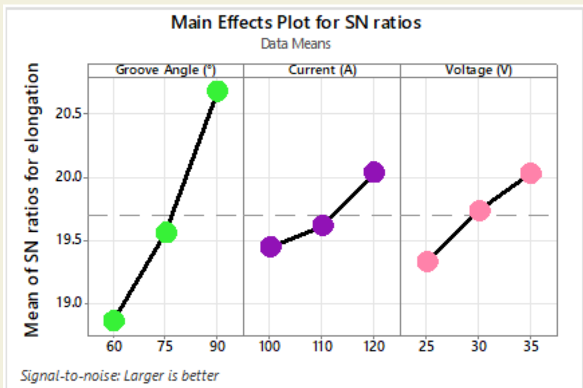


Figure 9. Main effects plot for S/N ratios (for elongation).

Table 9. Response table for S/N and significance for tensile strength and elongation.

Tensile strength (MPa)							
Response table for signal to noise ratios				Response table for means			
Larger is better				Larger is better			
Level	Groove Angle (°)	Current (A)	Voltage (V)	Level	Groove Angle (°)	Current (A)	Voltage (V)
1	52.84	53.72	53.26	1	440.5	491.1	462.8
2	54.22	53.78	54.08	2	514.6	490.8	510.1
3	54.89	54.45	54.62	3	557.0	530.2	539.2
Delta	2.05	0.73	1.36	Delta	116.4	39.4	76.4
Rank	1	3	2	Rank	1	3	2
Elongation (%)							
Response table for signal to noise ratios				Response table for means			
Larger is better				Larger is better			
Level	**Groove Angle (°)**	**Current (A)**	**Voltage (V)**	**Level**	**Groove Angle (°)**	**Current (A)**	**Voltage (V)**
1	18.86	19.45	19.33	1	8.776	9.445	9.279
2	19.56	19.61	19.74	2	9.512	9.584	9.778
3	20.68	20.03	20.07	3	10.830	10.089	10.060
Delta	1.82	0.59	0.70	Delta	2.054	0.644	0.781
Rank	1	3	2	Rank	1	3	2

Table 10. ANOVA results for tensile strength and elongation.

Tensile strength (MPa)							
Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Groove Angle (°)	2	20837.9	62.75%	20837.9	10418.9	55.83	0.018
Current (A)	2	3077.4	9.27%	3077.4	1538.7	8.24	0.108
Voltage (V)	2	8921.4	26.86%	8921.4	4460.7	23.90	0.040
Error	2	373.3	1.12%	373.3	186.6		
Total	8	33210.0	100.00%				
R-sq: 98.88%		R-sq(adj): 95.50%			R-sq(pred): 77.24%		
Elongation (%)							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Groove Angle (°)	2	6.4970	75.58%	6.4970	3.2485	13.80	0.038
Current (A)	2	0.6896	8.02%	0.6896	0.3448	1.47	0.206
Voltage (V)	2	0.9383	10.92%	0.9383	0.4692	1.99	0.134
Error	2	0.4707	5.48%	0.4707	0.2353		
Total	8	8.5956	100.00%				
R-sq: 94.52%		R-sq(adj): 85.10%				R-sq(pred): 75.66%	

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

factors on the tensile strength and elongation values obtained by the Taguchi method confirm the results obtained from the experimental studies. When the main effects graphs for S/N ratios are examined, the values closest to the vertical gain importance. Because these values represent the most effective parameters. Groove angle were seen as the most effective parameters for tensile strength and elongation.

3.3. Analysis of the variance (ANOVA)

In this study, the ANOVA was used to analyse the effects of groove angle, current and voltage on damage factors, tensile strength and elongation. This analysis was performed at a 95% confidence level and 5% significance level. In the ANOVA analysis, the F values of each control factor are compared and thus the significance of the control factors is determined [4, 28, 31]. The ANOVA analyse results for tensile strength and elongation are given in Table 10.

As can be seen in Table 10, based on the percent additive rates, the most effective factor for tensile strength and elongation was determined to be groove angle. These additive values for tensile strength and elongation were 62.75% and 75.58%.

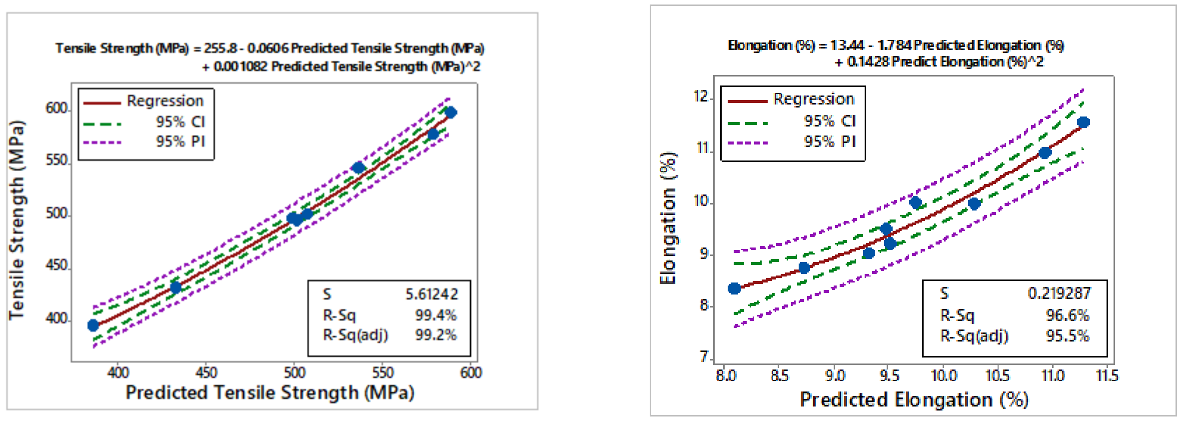
3.4. Analysis of the regression

Regression analyses are carried out in order to analyse and model different variables that have a relationship between one or more independent variables and a dependent variable [4, 28, 31]. In study, the equations for estimations of tensile strength and elongation were found by regression analysis. Equation estimates were made to be linear models. Estimated linear equations for tensile strength and

Table 11. Estimated linear equations.

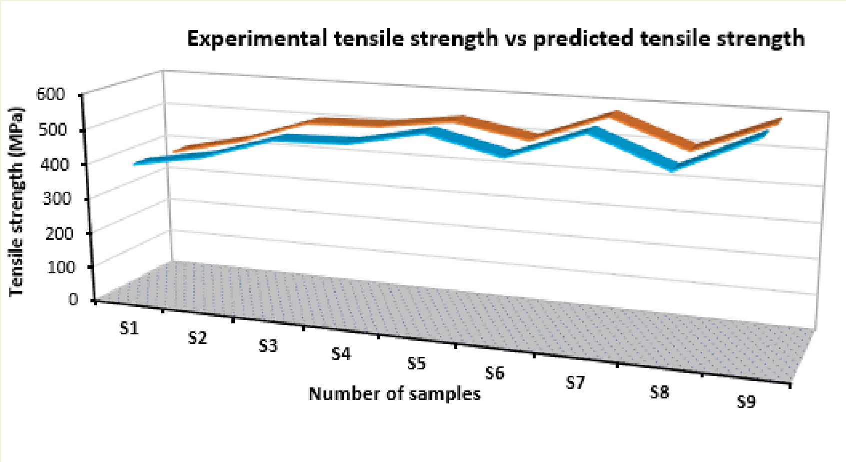
Current (A)	Voltage (V)	Estimated linear equations
120	30	Tensile Strength (MPa) = 245.2 + 3.881 Groove Angle (°)
120	35	Tensile Strength (MPa) = 274.3 + 3.881 Groove Angle (°)

Elongation (%) = 9.706 - 0.930 Groove Angle (°) - 0.194 Groove Angle (°) _75 + 1.124 Groove Angle (°) _90 - 0.261 Current (A)_100 - 0.122 Current (A)_110 + 0.383 Current (A)_120 - 0.427 Voltage (V)_25 + 0.072 Voltage (V)_30 + 0.354 Voltage (V)_35



(a) (b)

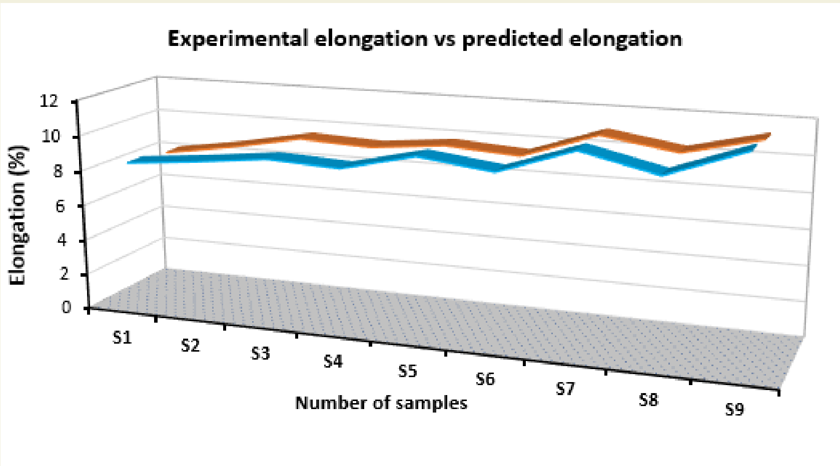
Figure 10. The experimental results vs predicted values.



	S1	S2	S3	S4	S5	S6	S7	S8	S9
Exp. Tensile Strength (MPa)	395.125	431.199	495.287	501.234	545.299	497.325	576.997	495.945	597.963
Predicted Tensile Strength (MPa)	386.370	433.400	501.839	507.786	536.544	499.526	579.198	502.497	589.208

Exp. Tensile Strength (MPa) Predicted Tensile Strength (MPa)

(a)



	S1	S2	S3	S4	S5	S6	S7	S8	S9
Exp. Elongation (%)	8.354	8.752	9.221	9.031	10.011	9.495	10.949	9.989	11.551
Predicted Elongation (%)	8.091	8.732	9.513	9.325	9.741	9.471	10.922	10.281	11.287

Exp. Elongation (%) Predicted Elongation (%)

(b)

Figure 11. Comparison of experimental and predicted values for tensile strength and elongation.

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elongation is given in Table 11. As can be seen, the two best equations for tensile strength are shown.

The experimental results versus predicted values for output parameters are given Fig. 10 a and 10 b.

As can be seen in Figures 10 and 10b, a very good correlation was found between the test results and the predicted results. The R^2 values of the equations obtained for the average elongation and tensile strength were found to be 96.6% and 99.4%.

Fig. 11 a and 11 b show a comparison of experimental values and predicted values for elongation and tensile strength.

4. Conclusions

In this study, it was aimed to analyse the tensile strength and elongation of medium carbon steel rod joints joined by MIG welding and to optimize the input parameters with the help of Taguchi method to obtain good mechanical properties. As a result, Taguchi method has been carried out successfully to obtain best MIG welding parameters. The results of the study are given below.

- In the tests, the highest tensile strength as 597.963 MPa was obtained at groove angle 90°, current 120 A and voltage 30 V. The lowest tensile strength was measured as 395.125 MPa. The results showed that the highest tensile strength was 51.33% higher than the lowest tensile strength value. In addition, the average tensile strength of joints was measured as 504.042 MPa.
- The tensile strength values tend to increase depending on the increase in the groove angles. In the tensile tests of the joints, the tensile strength value of the 90° groove angled was 20.73% higher than the tensile strength value of the 60° groove angled.
- The highest elongation as 11.551% was obtained at groove angle 90°, current 120 A and voltage 30 V. The lowest elongation was measured as 8.354%. The results showed that the highest elongation was 38.30% higher than the lowest elongation value. In addition, the average elongation of joints was measured as 9.706%.
- the tensile strength and elongation values are generally positively affected by the welding parameters current and voltage increase.
- Based on S/N ratios, the optimal parameters for average tensile strength and elongation were A3B3C2.
- Based on ANOVA, the most effective parameters on average tensile strength were determined to be groove angle (62.75%), followed by voltage (26.86%), Current (9.27%), respectively. In addition, the most effective parameters on average elongation were determined to be groove angle (75.58%), followed by voltage (10.92%), Current (8.02%), respectively.

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