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Optimization of Nd:YAG Laser Welding Factors of Cold Rolled Strenx 700 CR Steel by Taguchi Method

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Abstract

In this study, cold rolled Strenx 700 CR steel with a minimum yield strength of 700 MPa, which is typically used in load bearing structures to produce stronger and lighter structures, is butt welded with Nd:YAG laser welding. The effect of welding factors on tensile strength is investigated by using laser power rate (20%, 40% and 60%), pulse duration (2, 4 and 6 ms) and pulse frequency (3, 5 and 7 hz). By using Taguchi L9 orthogonal experimental design, the number of experiments, which should be 27 when full factorial, is reduced to 9 experiments. The tensile strength test results are optimized by the Taguchi method's larger is better control characteristic. The optimum test combination for maximum tensile strength is determined as A3B2C2 (60%-4 ms-5 hz). The effect of the welding factors on the tensile strength results is analyzed using the analysis of variance (ANOVA) method and it is found that the most effective factor is the laser power rate with 84.26%.

Keywords: Nd:YAG laser welding, Strenx 700 CR steel, Taguchi method, Optimization, ANOVA

Soğuk Haddelenmiş Strenx 700 CR Çeliğinin Nd:YAG Lazer Kaynak Faktörlerinin Taguchi Yöntemi ile Optimizasyonu

Öz

Bu çalışmada, daha güçlü ve hafif yapılar üretmek için tipik olarak yük taşıyıcılarda kullanılan ve minimum 700 MPa akma dayanımına sahip soğuk haddelenmiş Strenx 700 CR çeliği Nd:YAG lazer kaynağı ile alın şeklinde birleştirilmiştir. Birleştirme işlemlerinde; lazer güç oranı (20%, 40% ve 60%), darbe süresi (2, 4 ve 6 ms) ve darbe frekansı (3, 5 ve 7 hz) kullanılarak, kaynak faktörlerinin çekme dayanımına etkisi incelenmiştir. Taguchi L9 ortogonal deney tasarımı kullanılarak tam faktöriyel iken 27 adet olması gereken deney sayısı 9 adet deneye indirgenmiştir. Çekme dayanımı testi sonuçları Taguchi

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metodunun en büyük-en iyi kontrol karakteristiği ile optimize edilmiştir. Maksimum çekme dayanımı için belirlenen optimum test kombinasyonu, A3B2C2 (60%-4 ms-5 hz) olarak belirlenmiştir. Çekme dayanımı sonuçlarına, kaynak faktörlerinin etkisi ise varyans analizi (ANOVA) metodu kullanılarak incelenmiş ve en etkin faktör %84.26 ile lazer güç oranı olduğu tespit edilmiştir.

Anahtar Kelimeler: Nd:YAG lazer kaynağı, Strenx 700 CR çeliği, Taguchi yöntemi, Optimizasyon, ANOVA

1. INTRODUCTION

Steel is one of the most significant structural materials in the world, hence innovations in structural steels have industrial consequences on a global scale. The industry is always trying to decrease weight, increase performance, safety, and production techniques. The usage of ultra-high-strength steels (UHSSs) with good formability and weldability is becoming an increasingly popular method for achieving these goals. The advantages inspire many technical sectors, especially the building and automotive industries, to seek out new applications for steel of greater quality. Structural steels with a high yield strength are known as high strength steels (HSS). Furthermore, steels having a yield strength greater than 700 MPa are regarded as UHSSs [1,2].

The transportation sector is progressing to a new level with an increasing variety of materials. High-strength fine-grain steels are preferred materials for vehicle structural elements because they have higher mechanical qualities than traditional steels [3,4]. The use of new steel grades, including high-strength fine grain steels of the Strenx type, will be dependent on their good weldability. Therefore, the tensile strength of welded joints of such steels is an important research topic.

Nowadays, laser welding is commonly preferred technique due to its obvious advantages in industrial applications, such as high precision, high productivity, high power density, high beam quality, adaptability, and automation adaptability [5,6]. The Neodymium-Doped Yttrium Aluminum Garnet (Nd:YAG) laser is one of the most widely preferred lasers because of its capacity to produce high quality welds at relatively high speed [7]. Due to its high energy density and low heat input, Nd:YAG laser welding offers the advantage of low deformation and a narrow heat affected zone in welded parts [8,9]. In this welding method, especially the precise control of the welding factors provides great advantages [10].

In manufacturing industries, many optimization methods are used to obtain the most suitable welding factors with the developing technology. One of the most widely used optimization methods for material applications is the Taguchi method. Taguchi method stands out among other optimization methods with its many advantages such as simplicity, applicability and cost-effective solutions [11]. In this study, the Taguchi design of experiments (DOE) approach is used to evaluate the effects of different welding factors such as laser power rate, pulse duration, and pulse frequency on the tensile strength of cold rolled Strenx 700 CR steel joined by Nd:YAG laser welding. In addition, Taguchi optimization is used to identify the optimal welding factors. Significance levels of the welding factors are also obtained using analysis of variance (ANOVA). In the conclusion section of the paper, suggestions for future studies are made based on the findings obtained.

2. MATERIAL AND METHOD

2.1. Material

In this research, cold-rolled Strenx 700 CR structural steel is used for welding production. The utilized steel sheet has a thickness of 1.2 mm and is commercially available. The tensile test results and chemical composition of the Strenx 700 CR material are detailed in Table 1. Moreover, the carbon equivalent of the steel utilized is presented in Table 1 as 0.41.

Table 1. Tensile test results chemical composition of Strenx 700 CR steel (% wt.)

<table>
<tr><td rowspan="2">Tensile test</td><td colspan="2">Yield strength Rp0.2 [MPa]</td><td colspan="2">Tensile strength Rm [MPa]</td><td colspan="2">Elongation A_{80} [%]</td></tr>
<tr><td colspan="2">836</td><td colspan="2">1142</td><td colspan="2">11.5</td></tr>
<tr><td rowspan="4">Chemical composition</td><td>C</td><td>Si</td><td>Mn</td><td>P</td><td>S</td><td>Cr</td></tr>
<tr><td>0.151</td><td>0.19</td><td>1.52</td><td>0.01</td><td>0.002</td><td>0.02</td></tr>
<tr><td>Ni</td><td>V</td><td>Cu</td><td>Al</td><td>$C_{ekv.}$</td><td>Fe</td></tr>
<tr><td>0.04</td><td>0.02</td><td>0.01</td><td>0.047</td><td>0.41</td><td>Balance</td></tr>
</table>

2.2. Method

2.2.1. Weld Sample Preparation

Commercially supplied large-sized sheets are laser cut into 100 mm x 220 mm pieces as part of the laser welding sample preparation studies. To achieve quality welding, it is crucial to connect these specimens to be butt-welded tightly before welding. For this purpose, we manufactured a specimen-fixing apparatus. Before welding, the plates are also cleaned to eliminate any potential surface contamination.

2.2.2. Laser Welding System

Laser welding studies are performed with the Sisma SWA 300 brand Nd:YAG laser device, the technical details of which are listed in Table 2. The assembly of laser welded joints is butt-joint type. During laser welding, argon shielding gas is utilized. The flow rate of argon gas is 4 lt/min. Laser focal length is 120 mm above the surface of the sheet. And the butt welding operations are carried out on both sides of the prepared specimens.

Table 2. Specifications of the laser welding system used in this study

Sisma SWA 300 Welding machine	
Average power	300 W
Maximum power	12 kW
Impact energy	150 J
Pulse frequency	0-100 Hz
Pulse duration	0.3-25 ms
Beam diameter	0.6-2 mm

2.2.3. Taguchi Method

In this study, the Taguchi approach is used to optimize the factors (laser power rate, pulse duration, and pulse frequency) that influence the tensile strength properties of laser-welded joints. Minitab 20.3 statistical software program is used for optimization and analysis studies [12]. As the number of factors influencing the tensile strength properties increases, the number of necessary tests also rises. This increases costs and complicates the application process. In conclusion, the Taguchi approach is applied, which is effective in scenarios involving multiple factors where decisions must be made. In this procedure, an orthogonal array is selected based on the total degrees of freedom (Total DoF) calculated by adding the DoF values for each factor [13,14].

In this study, 3 levels are selected for each of the 3 factor values. The total DoF value for each factor is obtained by subtracting 1 from the levels of the factors. There are 6 total DoFs for 3 levels of 3 factor values (see Table 3). The numbering of the samples indicating the levels of welding factors and the experimental design selected using Taguchi L9 orthogonal array are given in Table 4. Experimental results are converted to signal-to-noise (S/N) ratio in the Taguchi method. In data analysis, the S/N ratio is used to allow control of the response and reduce the variability associated with the response. In the Taguchi method, the S/N ratio has three performance criteria: minimum (smaller-the-better), maximum (larger-the-better) and average (nominal-the-best). In this study, objective functions are defined for maximum tensile strength. Equation 1 is used for maximum performance values [15-17].

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

Where n is the number of tests and y_i is the number of observed experimental data for the performance characteristics.

Table 3. Welding factors and levels used in the study

Factors	Unit	DoF	Level 1	Level 3	Level 3
A-Laser power rate	%	2	20	40	60
B-Pulse duration	ms	2	2	4	6
C-Pulse frequency	Hz	2	3	5	7
Total DoF	---	6	---	---	---

Table 4. Taguchi L9 orthogonal experiment design

Orthogonal array	Test number	A-Laser power rate [%]	B-Pulse duration [ms]	C-Pulse frequency [Hz]
A1B1C1	1	20	2	3
A1B2C2	2	20	4	5
A1B3C3	3	20	6	7
A2B1C2	4	40	2	5
A2B2C3	5	40	4	7
A2B3C1	6	40	6	3
A3B1C3	7	60	2	7
A3B2C1	8	60	4	3
A3B3C2	9	60	6	5

2.2.4. Tensile Test

Tensile test specimens are prepared perpendicular to the weld direction in accordance with ASTM, E8/E8M standard (see Figure 1). To determine the tensile strength of the welded specimens, tensile tests are performed on a computer-controlled UTEST-7014 tensile-compression testing machine at room temperature and a constant crosshead displacement speed of 5 mm/min. In order to ensure the accuracy of the tensile test results, the data at each level are obtained by averaging five test results. Standard deviations are also provided.

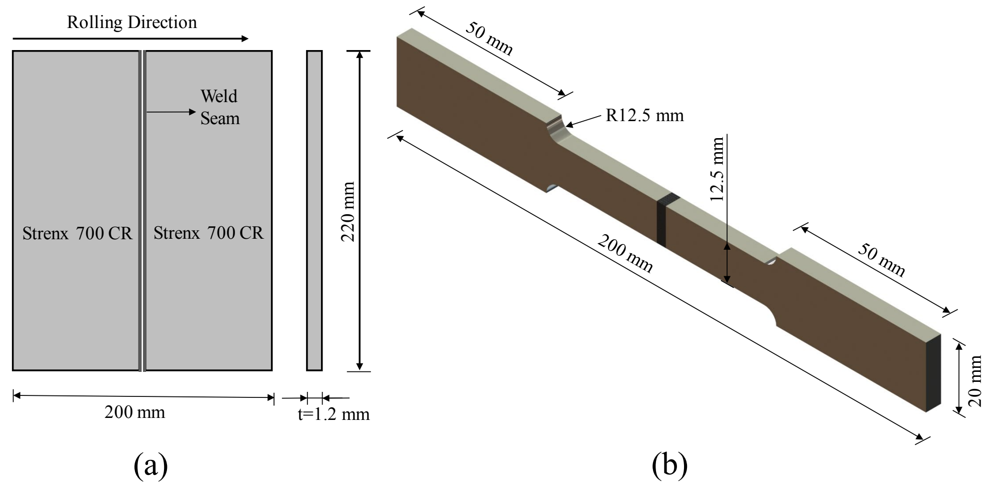

Figure 1. (a) Schematic representation of laser welded sheets, (b) Tensile specimen produced in accordance with the specifications (ASTM, E8/E8M)[18]

3. RESULTS AND DISCUSSION

3.1. Tensile Test Results

The tensile strength values obtained as a result of the experiments performed according to the experimental setup created within the scope of the Taguchi L9 orthogonal series are converted into S/N ratio and expressed in decibels (dB) by using the Taguchi method [19]. Tensile strength and S/N ratios are given in Table 5. The aim of this study is to obtain the highest tensile strength values. The specimen with the highest tensile strength among all specimens is A3B2C1 with 953.33 MPa. The laser power rate is 60%, the pulse duration is 4 ms, and the pulse frequency is 3 hz for this specimen's welding.

Table 5. Tensile strength values with the calculated S/N ratios of the welded joints

Orthogonal array	Tensile strength [MPa]	Standard deviation	S/N Rate
A1B1C1	628.0	32.36	55.9592
A1B2C2	764.0	23.05	57.6619
A1B3C3	740.67	29.7	57.3925
A2B1C2	859.5	10.5	58.6849
A2B2C3	910.67	35.39	59.1872
A2B3C1	939.5	31.67	59.4579
A3B1C3	892.5	9.98	59.0122
A3B2C1	953.33	38.42	59.5849
A3B3C2	948.25	13	59.5385

3.2. Optimization of Results with Taguchi Method

The table showing the change of S/N ratio of tensile strength according to "Larger is better" is given in Table 6. In addition, the results of the control factors mentioned in Table 6 are presented graphically in Figure 2. The best value for any factor is found based on the highest S/N ratio obtained among all levels of that factor. According to the graphical representation of the S/N ratios shown in Table 6, the optimum test combination determined for maximum strength is A3B2C2. This result shows that optimum tensile strength is achieved for high values of laser power ratio and medium values of pulse duration and frequency. According to the delta values, the order of the effects of the parameters on the tensile strength is 1, 2 and 3.

Table 6. Response table for the S/N ratios for the tensile strength (Larger is better).

Level	A-Laser power rate	B-Pulse duration	C-Pulse frequency
1	57.00	57.89	58.33
2	59.11	58.81*	58.63*
3	59.38*	58.80	58.53
Delta	2.37	0.93	0.29
Rank	1	2	3

*Optimum level

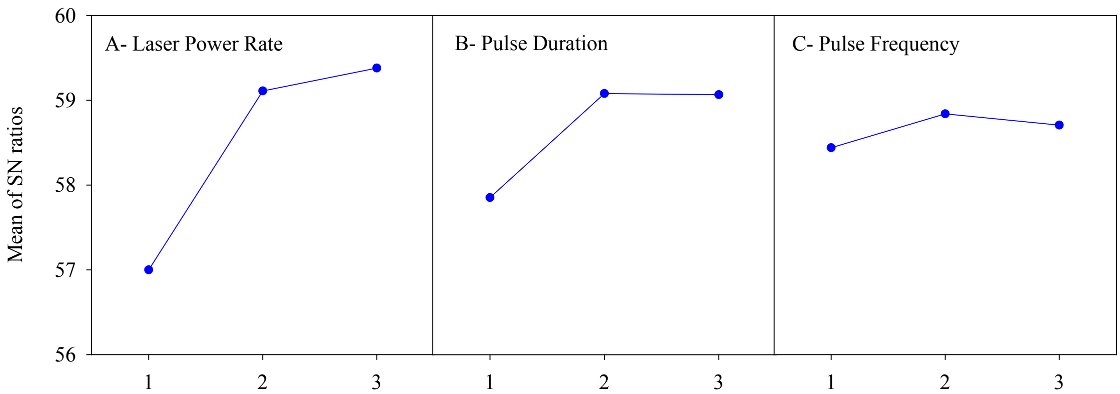

Figure 2. S/N ratio graph of control factors for tensile strength

3.3. Evaluation of Factors with ANOVA

ANOVA statistical methods are used to analyze and interpret the data obtained in the experimental studies and to make decisions on the results. ANOVA analysis is a statistical method that allows to examine the interaction of independent variables with each other and defines the difference between them [20]. In this study, since the effects of three factors on one variable are examined, the One-Way ANOVA method is preferred. Variance tables for tensile strength are shown in Table 7. The percentages of the laser welding factors affecting the tensile strength are given in the same table. The percentage contribution of the welding factors is also shown graphically in Figure 3.

ANOVA determines the ratio between the regression mean square and the mean square error and is called the F ratio or variance ratio. This ratio is also a factor due to the error term and a ratio due to the effect of variance. If the calculated value of the F ratio is high, the factor is significant at the desired level. In general, when the F value increases, the importance of the particular factor and its contribution the percentage also increases [21]. When the effect of welding factors is analyzed through ANOVA results, it is observed that the most effective welding factor on tensile strength is the average power rate with a rate of 84.26%. It is noticeable that the effect of pulse duration is around 13%. Compared to other factors, pulse frequency has the lowest effect on tensile strength with 0.823%. The residual error rate is found to be 1.97% as well.

Table 7. Analysis of variance (ANOVA) results for tensile strength S/N ratios

Source	(DoF)	Adj SS	Adj MS	F-Value	Contribution [%]
A-Laser power rate	2	86391	43195.4	42.87	84.26
B-Pulse duration	2	13691	6845.4	6.79	13.35
C-Pulse frequency	2	433	216.7	0.22	0.42
Residual error	2	2015	1007.6	---	1.97
Total	8	102530	---	---	100

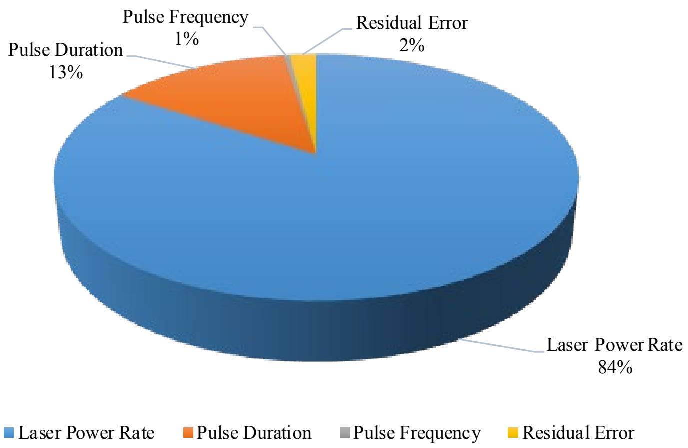

Figure 3. Effect of factors on tensile strength as a percentage

3.4. Verification of Experiments

In the experimental study using Taguchi optimization method, optimal results of tensile strength values are obtained. Sometimes these results can be any of the existing experiments, and sometimes they can be the results of an experiment other than the experiments performed [22]. In this study, a different optimum result is found from the experiments performed. The optimum result for tensile strength is reached in A3B3C2 experimental conditions different from the existing experiments. In this direction, the values obtained as a result of the calculations, where the optimal conditions are estimated, and the tensile strength values obtained as a result of the verification tests are presented in Table 8. The results obtained from the validation experiment reflect the success of the optimization. The tensile strength obtained as a result of the verification tests is measured as 969.33 MPa. Thus, an improvement of 1.68% is achieved at the end of optimization compared to the tensile strength value obtained in the initial experiments (953.33). When the results of the verification experiment are examined, it is seen that the result obtained for the estimated welding factor is sufficient and Taguchi optimization is successfully applied.

Table 8. Optimum results and validation experiment results

Optimum level: A3B2C2	Predicted value [MPa]	Experimental result [MPa]
	967.628	969.33
Prediction error [%]	0.18	

4. CONCLUSIONS

In this study on the optimization of the tensile strength of 1.2 mm thick Strenx 700 CR sheets joined by Nd:YAG laser welding using the Taguchi method, the following results are obtained as a result of the experiments performed.

- In the experimental studies, Taguchi L9 experimental design and optimization is successfully applied for the Nd:YAG laser welding process of Strenx 700 CR sheets.

- The best tensile strength value (969.33 MPa) is achieved at 60% laser power rate, 4 ms pulse duration and 5 hz frequency value.

- According to the ANOVA results, it is determined that the most effective factor on the tensile strength value is the laser power rate with a rate of 84.26%, the pulse duration is the second effective factor with a rate of 13.35%, and finally the factor with a much lower effect than the others isthe pulse frequency with a rate of 0.42%.

- After Nd:YAG laser welding performed under optimum conditions, the predicted and experimental weld strength values are 967.628 MPa and 969.33 MPa respectively. The prediction error is 0.18%.

- In future studies, higher laser power rates can be tested to check their effects on tensile strength.

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