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OPTIMIZATION OF WELDING PARAMETERS OF ELECTRICAL RESISTANCE SPOT WELDED 6082-7075 ALUMINIUM JOINTS USING THE TAGUCHI METHOD

OPTIMIZACIJA PARAMETROV ELEKTRO-UPOROVNEGA TOČKOVNEGA VARJENJA ZLITIN NA OSNOVI ALUMINIJA TIPOV 6082 IN 7075 S POMOČJO TAGUCHIJEVE METODE

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In this study, aluminium alloys of AA6082 and AA7075 series were welded with resistance spot welding. Effects of welding current intensity, welding time, and electrode pressure on the tensile strength and microstructure were examined, and their optimized values were determined using the Taguchi method. While performing optimization, the L_{24} orthogonal array was used with the Taguchi method. With this array, the signal/noise (S/N) ratio became the determining factor in controlling the optimization results. Comparing the experimental procedures and analysis results, the results obtained from the real application and Taguchi analysis were found out to be similar.

Keywords: resistance spot welding, aluminium, Taguchi method

V članku avtorji opisujejo medsebojno varjenje dveh vrst pločevin iz različnih Al zlitin tipa AA6082 in AA7075 s postopkom točkovnega električnega uporovnega varjenja. Raziskovali so vpliv intenzitete izbranega električnega toka, časa varjenja in tlačne sile elektrode na kakovost nastalih zvarov glede na njihovo natezno trdnost in nastalo mikrostrukturo. S pomočjo Taguchijeve metode in matrike L_{24} so določili optimalne parametre varjenja. V tej matriki je razmerje signal/šum (S/N; angl.: signal/noise ratio) uporabljeno kot kontrolni parameter rezultatov optimizacije. Primerjava obeh metod; eksperimentalnih postopkov in Taguchijeva analiza je dala podoben končni rezultat.

Ključne besede: elektro-uporovno točkovno varjenje, zlitine na osnovi aluminija, Taguchi metoda

1 INTRODUCTION

Material science, technologies and manufacturing methods are constantly evolving in order to meet the requirements of technology and human needs in the globalizing world. Therefore, various materials have been developed as alternatives to the conventional materials such as iron and steel. One of these materials is aluminium and its alloys. With advancement in technology, it is used in fields like construction, defence, transportation and energy, rather than for common daily applications. The development of joining methods is of great importance as well. Although aluminium is more difficult to weld with electrical resistance than steel due to its narrower plastic change zone and higher thermal and electrical conductance, aluminium is preferred in the automotive industry due to its low density, relatively high strength and light structural weight.[1,2] In addition, aluminium is also preferred due to its low exhaust emissions, leading to reduced greenhouse gas effects and fuel savings in the context of increasing fuel prices.[3,4] With the increase in aluminium use in the automotive sector, welding methods began to diversify. One of them is resistance spot welding, a method that is suitable for the serial and robotic automation, and generally used in the automotive industry. Also, this welding method is rapid, inexpensive, controllable in terms of joining quality, and high-performing. This advancement in technology also enabled the joining of aluminium with resistance spot welding. Here, welding current, welding time and welding electrode pressure are the most important parameters.

This method is one of the most common joining techniques in the welding of sheets with different thicknesses and, consequently, different joint structures used in the automotive industry[5]. An average vehicle can have 2000–5000 resistance welding joints.[6,7] These numbers demonstrate the importance of resistance spot welding in the production. During welding, the electrode forces squeeze the sheets and the heat produced by electrical resistance passes between the electrodes and the plates, al-

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lows the joining process to occur.[8,9] Even though various methods such as TIG, MIG, laser and friction stir welding are used in the industry, resistance spot welding continues to maintain its place in the automotive industry.[10,11] Transmission of electrical energy and control of energy are important elements during a welding process. Generally, two types of welding machines are used: AC and DC. AC machines are single-phase and operate at a low, fixed frequency, while DC machines are three-phase, with a medium-frequency input and adjustable output frequency.[12–14]

The Taguchi optimization is a statistical analysis program used in engineering to increase product quality, improve designs and reduce the number of experiments. In particular, reducing the number of experiments and improving the design make this application stand out. Obtaining a higher quality product faster and at lower costs with the Taguchi optimization method is an important step in increasing the quality in the field of engineering.[15] This system ensures that the production of a high-quality and appropriate product closely matches the desired outcome of the planned work or production process. In order to achieve the best results in the production process, with each change made in the parameters, the number of experiments and, consequently, their duration increase. With the Taguchi method, we can achieve this result with fewer experiments. To do this, the system uses a specific orthogonal array design to examine all process parameters. With this orthogonal array design, the user can determine the most suitable parameter types for production using the signal-to-noise (S/N) ratio, analysing experimental data and examining many parameters through average quality data and variations. At the same time, the signal-noise levels of the studies affect the optimized levels of the parameters. On the other hand, ANOVA is also applied in experimental studies. ANOVA is a statistical method variance analysis used to determine the order of parameters in experimental studies. It determines the parameter reliability interval and provides results as percentage ratios, indicating the relative importance of factors from least to most significant. With the Taguchi optimization, the accuracy of the experiments can be evaluated by performing experimental work (verification study) at the desired and closest values.[16,17]

Different studies are included in the available literature. Manufacturing studies of aluminium steel and different aluminium series were considered. Arghavani et al. examined the effect of a zinc layer on joining steel and aluminium in resistance spot welding.[18] Esme used this method to improve weld quality in resistance spot welding of steel sheets and assessed the suitability of the welded values by comparing them to the Taguchi values.[15] Li et al. carried out numerical and experimental investigations of the hot cracking phenomenon of AA6061/AA7075 different aluminium alloys joined with resistance spot welding. However, aluminium is more difficult to weld with electrical resistance than steel due to its narrower plastic change zone and higher thermal electricity.[19]

In this study, AA 6082-AA 7075 series aluminium samples were joined with resistance spot welding. The main parameters affecting resistance spot welding – welding current, welding time and electrode force – were optimized with the Taguchi method. The effects of the obtained results on the tensile strength, macrostructure and microstructure of the samples joined with resistance spot welding were investigated. During this optimization, the L24 orthogonal array was used with the Taguchi method. The signal/noise (S/N) ratio of this orthogonal array was the main factor for controlling the optimization results. When the results of the experimental procedures created with the Taguchi method were compared, it was determined that the experimental set-up created was successfully applied.

2 EXPERIMENTAL PROCEDURE

AA60682 and AA7075 aluminium alloys used in various fields of industry were joined with resistance spot welding. In the joining process, where compression and holding times were fixed, the welding current, welding time and electrode force were changed. Microstructure examination and tensile tests were performed for each applied parameter. The chemical compositions of the aluminium used in the experimental study are given in **Table 1**.

Table 1: Chemical compositions of the sheets used in the experimental study (*w*/%)

Material	Fe	Si	Mn	Cr	Ti	Cu	Mg	Zn
AA7075	0.12	0.06	0.03	0.18	0.05	1.7	2.7	5.8
AA6082	0.42	1.0	0.48	0.02	0.04	0.07	0.8	0.06

Test samples for resistance spot welding were prepared by cleaning the surfaces and assembling them. An electrode force of 2–4 kN was applied to all test pieces. Welding times were determined with preliminary experiments as 6, 8 and 10 periods. Welding processes were completed by applying welding current values in ranges of (25, 30 and 35) kA. Tensile shear samples and microstructure samples were prepared for the experimental studies. Microstructure samples were embedded in Bakelite, then ground, polished and etched. Keller's solution, which is commonly used for etching aluminium and its alloys, was prepared. For the tensile shear test, a Shimadzu tensile device with a capacity of 5 tons was used. The average value of the tensile tests was calculated as the nominal tensile value and entered into the Taguchi test design as result data.

3 RESULTS AND DISCUSSION

3.1 Microstructures

Since weld quality and strength are related to weld nugget size, microstructure studies and a metallography analysis provide more effective results about the microstructure and weld nugget dimensions of the weld area. **Figures 1a** and **1b** show two different macrostructures of base metal (BM), heat affected zone (HAZ) and core zone.

Figures 2 and 34 show the weld zone and microstructures under the influence of heat at different welding currents, 8 cycle welding time and 2 kN electrode pressure.

In **Figures 2a** and 2b, the density of dendritic structures in the weld region is shown. In **Figure** 2a, it is observed that the dendritic structure transitions from a dendritic grain structure into a co-grain structure as it approaches the AA6082 base metal region. During the transition from the dendritic structure to the AA7075 main metal region in **Figure 2b**, a wider HAZ transition is observed in the HAZ region compared to **Figure 2a**. The dendritic structure is similarly observed in **Figure 3a**. The transition from the welding area to the HAZ and the main material is evident. In **Figure 3b**, we can similarly see the transition from the weld region. In **Figure 1a**, we see the weld core of the sample at the 30 kA welding current intensity. Its ovality and weld core shape are similar to the macrostructures presented in the work by Li et al.[19] In **Figure 1b**, we see the weld nugget of the sample at the 35 kA welding current. The 30 kA and 35 kA current, 2 kN electrode force and 8 period welding time were kept constant. However, it was observed that at the 35 kA welding current, the weld core shifted more to the 7075 side. This situation is believed to occur due to different heat conduction coefficients of the mate-

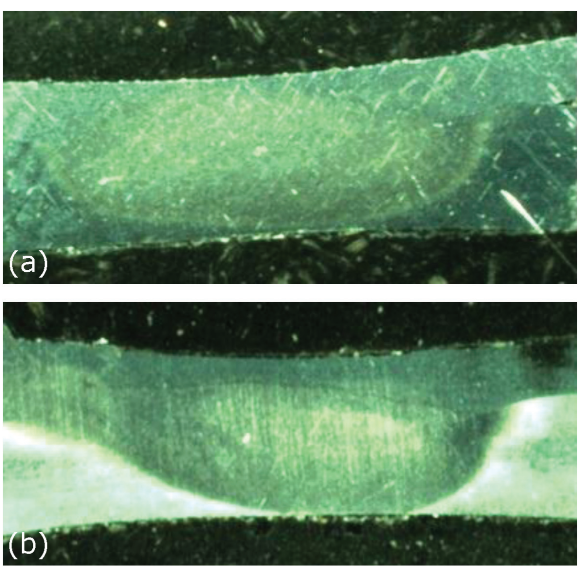

Figure 1: a) 30 kA, b) 35 kA macrostructures of BM: base metal, FZ: fusion zone, HAZ: heat affected zone

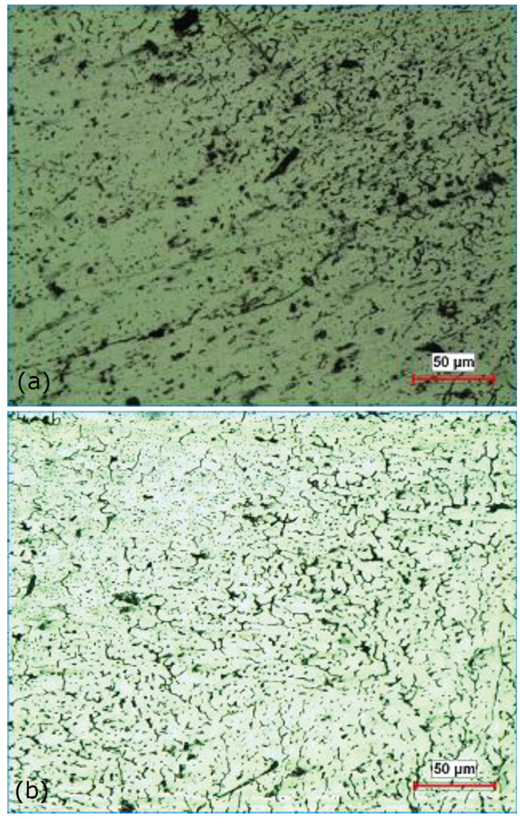

Figure 2: a) AA6082, b) AA7075 with a 30 kA core perimeter, heat-affected-zone columnar structure and large coarse grains

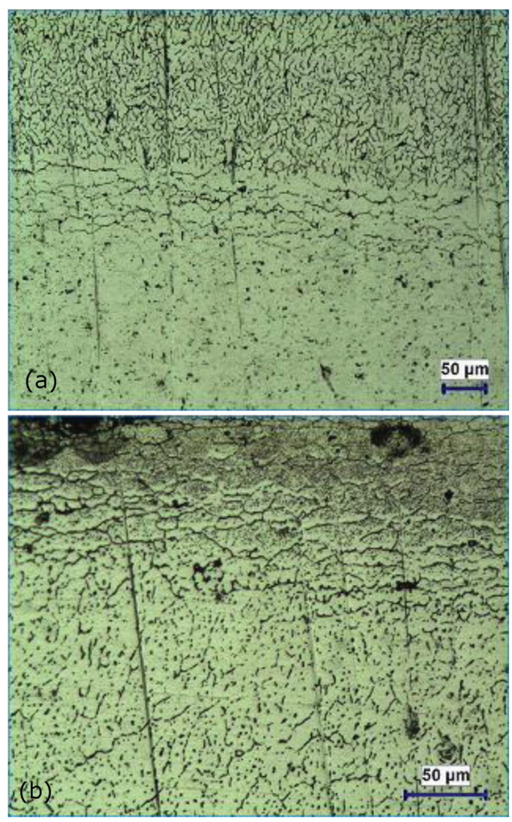

Figure 3: a) AA6082, b) AA7075 with a 35 kA core perimeter, heat-affected-zone columnar structure and large coarse grains

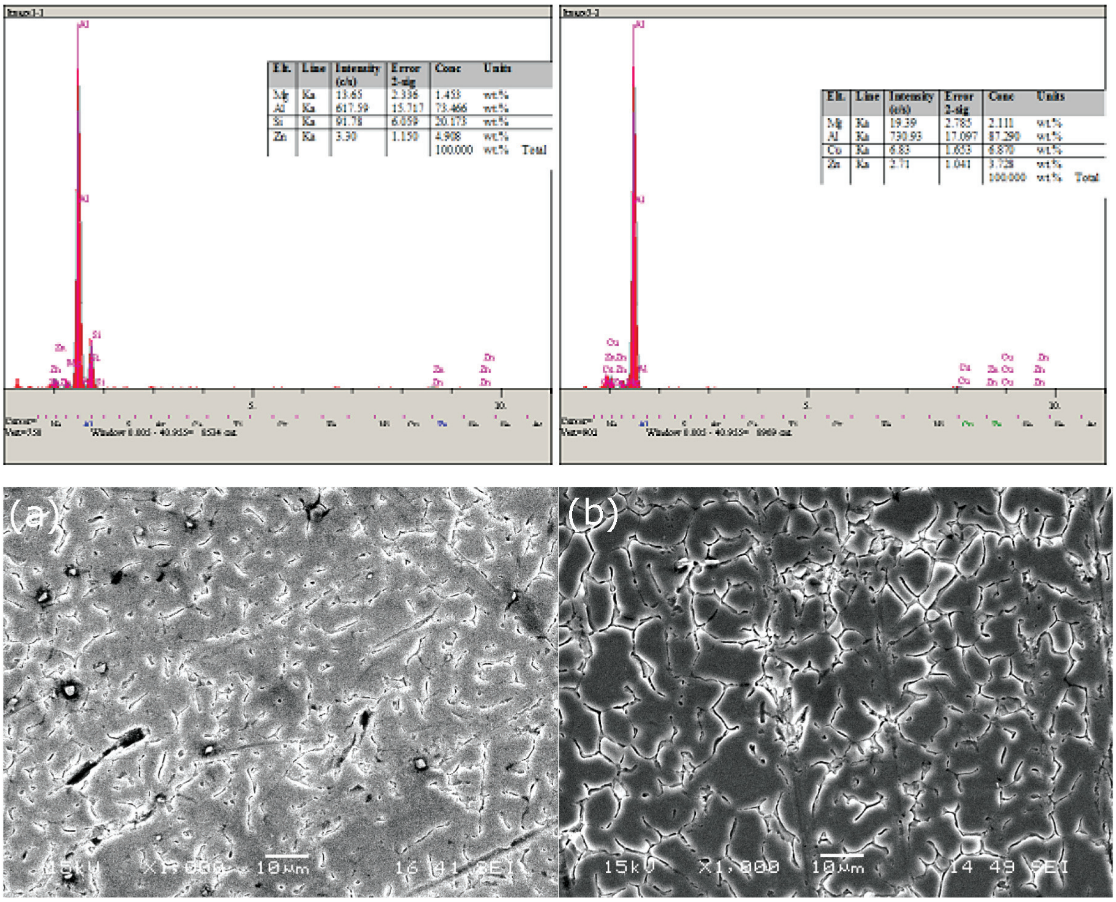

Figure 4: a) 30 kA welding SEM image of EDS analysis, b) 35 kA welding SEM image of EDS analysis

rials and also due to their different electrical resistivities.[20,21]

As shown by the EDS analysis, the microstructure distribution in the samples made at 30 kA aligns with the elemental ratios observed in the base metals. When we look at the EDS analysis of the samples made at 35 kA, there is an increase in the copper content. The 6082 aluminium/copper ratio is 0.07 % and the 7075 aluminium/copper ratio is 1.7 %. However, in the EDS analysis of the weld nugget of the sample made at 35 kA, the copper content reaches a value of 6.87 %. In this case, there is an extra copper input to the weld core. The macro images of copper reveal that, despite constant welding time and electrode force, excessive copper-electrode contact causes some copper to melt and mix with the weld metal due to heat.

3.2 Taguchi method

Establishing the correct experimental design is an important factor for accuracy in experimental studies. In this study, where aluminium was joined with resistance spot welding, the Taguchi L24 orthogonal array was used as the experimental set-up, along with the result analysis. In this approach, the statistical analysis method known as the signal-to-noise (S/N) ratio was used to analyse experimental data. This signal/noise ratio provides the verification value for the optimization process by minimizing the control factors in the Taguchi optimization, reducing the number of variables in the experimental process. In an experiment designed with the Taguchi method, variability is regulated by varying noise factors to ensure variability and determine, from the results, the optimum control factor settings that make the process, or product, resistant to the changes caused by noise. By minimizing these factors, the signal-to-noise ratio can be set to the highest level. The signal-to-noise ratio can show how different amounts of noise react under optimal conditions and how it should change according to the desired results. Depending on the desired result of an experimental study, different signal-to-noise ratios can be chosen. When using scaling factors, the average over the target can be adjusted without changing the signal-to-noise ratios. The software used for optimization processes calculates separate signal-to-noise ratio for each combination of control factor levels in the design. To obtain the desired experimental results in accordance with the Taguchi optimization, one can choose between different signal-to-noise ratios depending on the variables. With this selection, results closest to the desired result can be obtained. The S/N ratios to be selected for the optimization process can be: smaller is better, larger is better, and nominal is better.[22] This study was carried out on the basis of strength values and since these were desired to be high, S/N ratios were calculated based on "greatest is best" criterion. The formula below was used to calculate the S/N ratio. In this formula, "y_i" refers to the measured strength, "i" refers to the observation value, and "n" refers to the valid experiments in this study.

$$S/N = -10 \lg \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_1^2} \right) \quad (1)$$

Control factors and levels in joining AA6082 and AA7075 aluminium sheets with resistance spot welding are given in **Table 2**.

Table 2: Control factors and levels

Symbol	Control factors	Level 1	Level 2	Level 3
A	Electrode force (kN)	2	3	4
B	Welding current intensity (kA)	25	30	35
C	Welding time (cycle)	6	8	10
1 cycle = 0.02 sn				

Predictive values of S/N ratios calculated from the tensile shear results of the optimization experiment carried out in accordance with the Taguchi L_{24} experimental design for joining AA6082 and AA7075 samples with resistance spot welding are given in **Table 3**.

Table 3: Experimental design, tensile test and S/N ratios

No	(A) Current (kA)	(B) Time (Cycle)	(C) Force (kN)	Tensile strength (N)	S/N ratio (dB)	Estimated tensile value (N)
1	25	6	2	4074	72.2003	4214
2	25	6	3	3207	70.1214	3778
3	25	6	4	3085	69.7863	3285
4	25	8	2	3860	71.7327	4214
5	25	8	3	3529	70.9521	3779
6	25	8	4	3492	70.8619	3286
7	25	10	2	4940	73.8738	3836
8	25	10	3	4079	72.2103	3401
9	25	10	4	2435	67.7315	2908
10	30	6	2	4111	72.2788	4676
11	30	6	3	3963	71.9605	4241
12	30	6	4	3902	71.8259	3747
13	30	8	2	5028	74.0272	4976
14	30	8	3	4349	72.7688	4241
15	30	8	4	3653	71.2533	3748
16	30	10	2	4538	73.1373	4298
17	30	10	3	4108	72.2722	3863
18	30	10	4	3208	70.1256	3370
19	35	6	2	4047	72.1435	3682
20	35	6	3	3992	72.0231	3246
21	35	6	4	3241	70.2140	2753
22	35	8	2	3512	70.9110	3682
23	35	8	3	3179	70.0452	3247
24	35	8	4	3023	69.6098	2754
25	35	10	2	2473	67.8642	3304
26	35	10	3	2259	67.0792	2869
27	35	10	4	2185	66.7909	2376

In the Taguchi optimization, there is a separate S/N answer table for each factor for its definition and interpretation. This table provides reference results used for choosing the best level and ranks. These tables determine how the outputs affect the desired outcome in experimental studies. The answer table shows how the parameters in this study affect the tensile results. When the data in the table is examined, the highest values indicate optimum results in accordance with the largest-is-best option selected for the optimization.

Table 4: Experimental design, tensile test and S/N ratios

Level	(A) Welding current (kA)	(B) Welding time (Cycle)	(C) Electrode force (kN)
1	71.05	71.39	72.02
2	72.18	71.35	71.05
3	69.63	70.12	69.80
Delta	2.55	1.27	2.22
Rank	1	3	2

Considering the values given in **Table 4**, S/N ratios are A2B2C1. The optimum values for welding current intensity, welding time, and electrode force were 72.18 (Level 1), 71.35 (Level 2), 72.02 (Level 3), respectively. The main effect graphs created using the level values in this table are shown in **Figure 6**. As in the table of experimental design, tensile test and S/N ratios, the largest S/N values in the main effect graphs given in **Figure 6** show the optimum levels of the parameters used in resistance spot welding. In accordance with these values, optimum values were determined for the welding current intensity, welding time and electrode force in joining AA6082 and AA7075 samples with resistance spot welding.

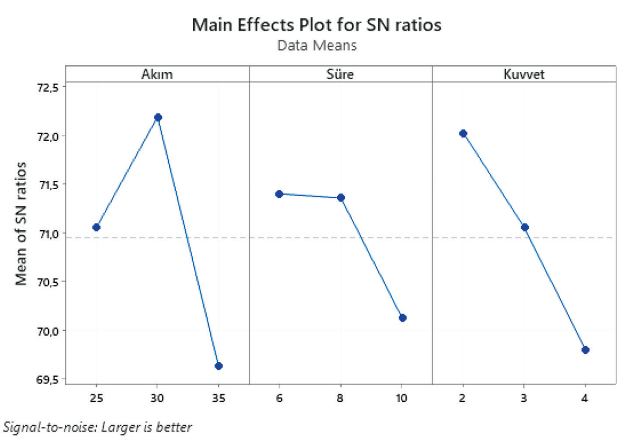

Figure 6: Main effect graphs for S/N ratios

Table 5: ANOVA results for tensile value S/N ratios

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	5794535	39.82 %	5794535	1931512	5.07	0.008
Current	1	1274170	8.76 %	1274170	1274170	3.35	0.080
Period	1	641077	4.41 %	641077	641077	1.68	0.207
Force	1	3879288	26.66 %	3879288	3879288	10.19	0.004
Error	23	8757926	60.18 %	8757926	380779		
Total	26	14552462	100.00 %				

3.3 Variance analysis (ANOVA)

Statistical analysis of variance (ANOVA) was applied to determine all control factors used in this study, examining their interactions, their impact on performance, the extent to which experimental parameters and variations influence performance, and the reasons for these changes.[23] ANOVA is a statistical application that provides significant results based on the analysis of experimental data. This application is very useful as it shows the significance level of the influence of factors, or the interaction between factors, on a particular response. ANOVA showed the contributions of the factors, variability, error rates and range of effects of the experimental values, which are given in **Table 5**. ANOVA calculates the ratio between the mean square error and the regression mean square, referred to as the F-value or variance value. This value is influenced by the effect of a factor and variance resulting from the error term. If the calculated ratio of the F-value is high, the factor is significant at the desired level. In general, when the F-ratio increases, the importance and contribution percentage of a particular factor also increases. ANOVA process was applied at 95 % reliability and 5 % significance levels. In determining the effect levels of the control factors used in the experiment, the F-ratio with the highest effect is determined as the ratio that affects the result the most. In determining this ratio, F-ratio results are compared with each other. When ANOVA results were examined, the most important parameter affecting the weld shrinkage value was electrode force with a ratio of 26.66. Welding current intensity was the second most effective parameter, with a ratio of 8.76. Finally, the parameter that had the lowest impact compared to the others was welding time with a rate of 4.41 %. Below, the sum of squares (SS), mean of squares (MS), F-values and percentage contribution rates (P) are shown, with DF values indicating the degree of freedom of each variable.

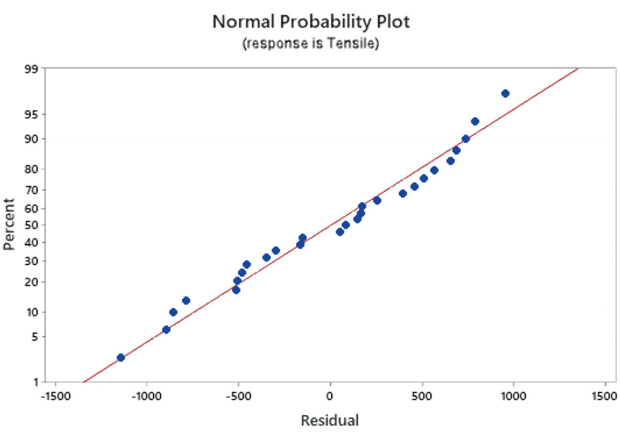

Figure 6: Comparison graph of the actual tensile values and estimated tensile values

3.4 Verification test

The last step in the optimization process with the Taguchi method is to estimate the change in weld-core mechanical properties using optimized resistance-spot-welding experimental-input levels and compare the results. The result comparison of the verified tensile test levels is given in **Table 6**. In this study, it was proven with the Taguchi optimization method that the resistance spot welding of AA6082 and AA7075 sheets changes with the changing of the parameters used during welding. The Taguchi optimization proved to be a simple and reliable method for determining the performance characteristics of tensile-shear values. In addition, **Figure 6** shows the verification chart of the prediction results obtained as a result of the analysis made with the Taguchi method, in comparison with the actual results.

Table 6: Verification test results

Estimated value	Experimental value	Variance
A2B2C1	A2B2C1	–
4976 N	5028 N	52
S/N 73.6422 dB	S/N 74.0272 dB	0.385

4 CONCLUSIONS

The results obtained with our experimental studies relating to the microstructure, macrostructure and optimization process are given below.

It was determined that AA6082 and AA7075 sheets can be welded.

Although the microstructures are generally dendritic, the grain growth was observed towards the HAZ region.

The electrical resistivity and thermal coefficients of the materials affected the formation region of the weld core.

Since the thickness cannot be changed in resistance spot welding of materials with different thicknesses, different electrode diameters can be applied.

A decrease in the strength values was observed after a certain increase.

The Taguchi L_{24} experimental design and optimization were successfully applied to the resistance spot welding of AA6082 and AA7075 sheets.

The best tensile shear strength value was achieved at the 30 kA welding current, 8 cycle welding time and 2 kN electrode force.

According to ANOVA results, the most effective of the tensile-shear parameters was the electrode force; the welding current was the second parameter, and the welding time was the third parameter.

The tensile strength was found to be the same after resistance spot welding performed under optimum conditions.

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