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Optimization of Resistance Spot Welding Parameters in Uncoated Cold-Rolled Steel by Using Taguchi Method

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Abstract

Objective: This study aims to evaluate the effects of spot-welding parameters specifically welding current, electrode force, and welding time on the tensile shear strength of 1.2 mm uncoated cold-rolled steel. The primary objective is to optimize these parameters to produce robust and reliable welded connections, especially in applications exposed to variable tensile-shear stresses. **Method:** The research utilized an L9 Taguchi orthogonal array to systematically randomize and analyze the effects of different process parameter configurations. The signal-to-noise (S/N) ratio was employed to identify the optimal welding parameters that maximize tensile shear strength. Additionally, Analysis of Variance (ANOVA) was used to assess the significance of each parameter's contribution to the tensile shear strength, providing a deeper understanding of the critical factors influencing weld quality. **Findings:** The optimal spot-welding parameters identified in this study are an electrode force of 2.1 kN, a welding time of 10 cycles, and a welding current of 6 kA. Among these parameters, electrode force emerged as the most critical factor influencing tensile shear strength, as demonstrated by ANOVA analysis. This finding highlights the importance of precise control over electrode force in achieving well-welded connections. **Novelty:** This research combines the Taguchi method with ANOVA to comprehensively examine and optimize spot-welding parameters for cold-rolled steel. By identifying electrode force as the most significant determinant of tensile shear strength, the study provides valuable insights into the optimization of welding processes. These findings are particularly relevant for industries such as automotive and manufacturing, where welded joints are subjected to rigorous stress conditions.

Keywords: Taguchi Method; Optimization; Resistance; Spot Welding; Electrode Force; ANOVA; Tensile Strength

1 Introduction

Resistance spot welding (RSW) is well well-known and extensively used linking method for sheet metal components in the automobile industry, and it is expected to stay that way for some time in the future. RSW is essential to the chemical, biomedical, shipbuilding, and automotive industries. It is thought to be a promising welding process because of its advantages of high productivity, cheap cost, and great efficiency[1]. Because of their appealing strength-ductility combinations, advanced high-strength steels, or AHSSs, are maximum frequently employed in basic components for automotive applications[2]. In numerous manufacturing industries, welding is a common manufacturing procedure. The advantages of using welding processes include the ability to create spot, butt, seam, lap, T, and corner joints, among other types of joining. The welding technique, which applies heat and pressure, can be used to create complex geometries and shapes out of diverse metals and thicknesses[3].

Weld quality deviations are caused by several intricate and interrelated elements, including material qualities, equipment conditions, and process variations, even when process parameters are set. These discrepancies have the potential to jeopardize performance and structural integrity, underscoring the urgent need for efficient quality assessment techniques[4]. The honesty and mechanical presentation of spot welds play a critical role in a vehicle's capacity to protect its occupants in the event of a collision. A spot weld transfers load to the vehicle assembly by acting as a fold starter in a collision. Thus, the total quality and reliability of a vehicle depend heavily on the mechanical presentation of the resistance spot welds[5].

RSW is a type of fusion welding in which heat is made by the materials' resistance to the electrical current movement. The automobile industry has made extensive use of high-strength steel owing to its benefits, which include a high strength-to-weight ratio that increases vehicle safety, improves fuel economy, and lowers CO2 emissions. Three primary factors are chosen to be altered that have an impact on welding quality: welding time, welding current, and electrode force. These parameters are necessary to achieve good welding quality. Numerous techniques have been employed to improve the tierce primary welding parameters. These approaches are helpful not solitary in guaranteeing high-quality welding nevertheless also in lowering manufacturing costs, particularly in the automotive sector. One of the greatest techniques for parameter optimization is the Taguchi design method, which can decrease the number of experiments by reorganizing the trials via an orthogonal array and identifying the maximum influential parameters [6-9]. Figure 1 shows the resistance spot welding.

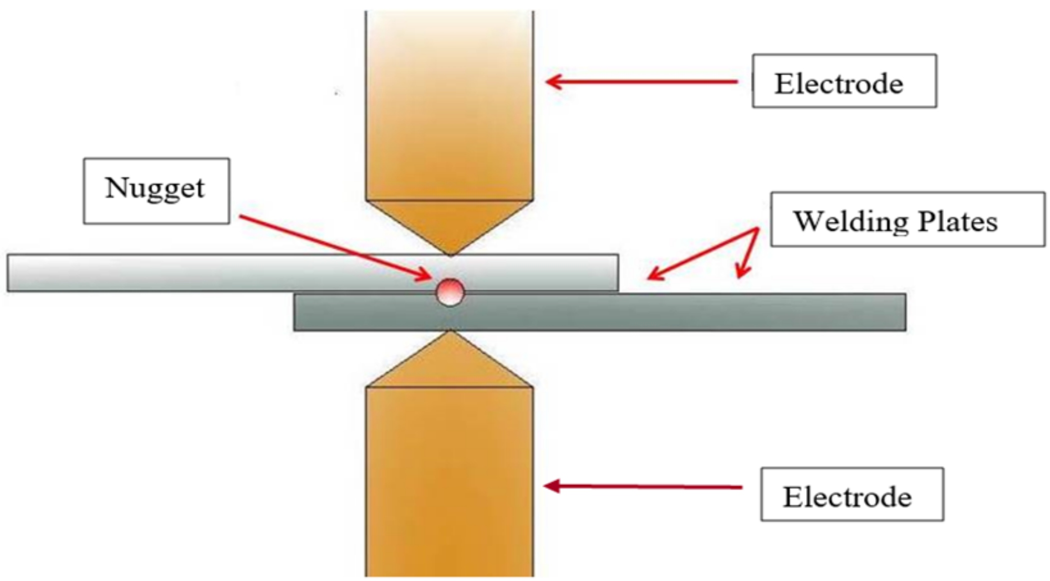

Fig 1. Resistance Spot Welding

Spot welding's advantages include its quick speed and adaptability to automation in high-rate or large-volume engineering. Despite these advantages, resistance spot welding reveals differences in quality between welds. The shear strength of joints was found to be significantly impacted by the type of filler used, the welding current, and the welding time. As the amount of current and weld nugget size increases, the joint strength drops. It was also discovered that two crucial elements that contribute to good metal weldability are welding currents and welding duration. A significant factor in the quality of the weld is the control of the welding settings[6]. Therefore, in this work the Taguchi Method's optimization of these parameters is required. The Taguchi method system was used to determine the parameter values that yield the greatest performance. In sequence reduce the effect of uncontrollable factors on system performance fluctuation, the ideal state is chosen. The welded specimen's tensile shear strength (TSS) will be further assessed using the three parameters welding current, electrode force, and welding time were selected.

1.1 Research Gap

Despite extensive research on optimizing resistance spot welding (RSW) parameters, most studies have primarily focused on coated steels or generalized approaches without isolating the specific effects of welding current, electrode force, and welding time on uncoated cold-rolled steel. Furthermore, while the Taguchi method has been widely used for process optimization, limited research has combined it with ANOVA to quantitatively assess the significance of each parameter's contribution to tensile shear strength. Existing literature often overlooks the dominant influence of electrode force compared to welding current and time, leading to suboptimal parameter selection. This study addresses these gaps by systematically identifying electrode force as the most critical determinant of tensile shear strength in uncoated cold-rolled steel, offering a more precise and reliable optimization strategy for industries reliant on robust welded joints.

2 Materials and Methodology

The type of specimen utilized in this investigation is uncoated cold-rolled steel. The workpiece's material is cut to the precise measurements of 1.2 mm in thickness, 55 mm in width, 100 mm in length, and 30 mm in contact overlap to prepare the samples. As shown in Table 1, the samples were ready for nine experiments with varying rates of welding current, electrode force, and welding time. There are three to four specimens in each trial. The reason for the variation in the no. of specimens in each test is that, after cutting the specimens to the same size, 3 specimens remain. These specimens were then utilized in the 5th, 8th, and 9th trials. Each trial includes a least of three specimens; trials with 4 specimens will yield better results and assist in determining the ideal parameter value.

Table 1. Count of specimens together with each parameter's details

Trial	Electrode force (kN)	No. of specimens	Welding time (cycles)	Welding current (kA)
1	2.1	3	10	6
2	2.5	3	15	8
3	3.0	3	20	10
4	2.1	3	10	6
5	2.5	4	15	8
6	3.0	3	20	10
7	2.1	3	10	6
8	2.5	4	15	8
9	3.0	4	20	10

A. Selection of orthogonal array

If there is a nonlinear relationship between the process parameters, it will only become apparent when considering more than two layers of parameters[7]. A robust design-based Taguchi approach states that an L9 orthogonal array is used in the experimentation. **Tables 2** and **3** contain tabular data on the chemical composition and mechanical assets, respectively.

Table 2. CR steel Chemical composition

Steel	(wt.%)			
	Si	C	Fe	Mn
Uncoated cold-rolled 1.59	0.20	Bal.	2.40	

Table 3. Mechanical Assets of CR steel

Steel	Elongation (%)	Ultimate Tensile Strength (Mpa)	Yield Strength (Mpa)
Uncoated cold-rolled	15	990	500

B. Welding

Utilizing a compact Resistance Spot Welding system with a 450V/50Hz weld voltage and 450kVA power input, two sheets were welded together. Employing a 6mm diameter electrode, welding experiments were conducted at currents of 6 kA, 8 kA, and 10 kA, with electrode forces ranging from 2.1 kN to 3.0 kN. Each specimen underwent 10, 15, or 20 welding cycles. Post-welding, the specimens were mounted using a thermostatic plastic forming method and a mounting press at approximately 150°C. The welded zones were revealed through etching using a 2% Nital etching reagent.

Starting at the lowest possible weld current and gradually increasing it until a spatter appears between the metal sheets is required. It signifies that the optimal welding current was achieved. The welding current's strength is measured in amperes using an ampere meter. The welding circuit may be turned off and the welding transformers may be destroyed if the welding power is too large [8]. Kim et al. [9] state that increasing the welding current and tensile load will also increase the residual stresses that are still present in the welded component. To prevent the accumulation of heat energy when welding a specimen thicker than 2 mm, it may be suitable to split the weld time by the number of impulses. Although this technique will result in a spot welding that looks nice, its strength may be lacking. Additionally, it has been noted that longer welding times result in more heat escaping the weld region [10]. This observation is consistent with [11]'s claim, as their study demonstrated that welding times, in addition to process temperature, significantly affect outcomes. Kocabekir et al. [12] explored the impact of welding time on the connectivity of welded 316L stainless steel, observing its influence on tensile shear load. They established a direct relationship between welding parameters and mechanical properties. Zhao et al. [13] highlighted the critical electrode force threshold for optimal mechanical properties in welded joints. Additionally, electrode force significantly affects joint failure energy absorption and tensile shear load capacity. Increasing electrode force maintains consistent conditions during welding, despite the growing interaction surface. However, adjusting electrode force as electrodes wear becomes challenging, often necessitating the selection of an average value.

C. Tensile Test

Tensile testing is done with the Universal Testing Machine. The specimen was clasped on both ends and dragged apart until it broke. The tensile test (tensile modulus) measures the specimen's tensile strength, stiffness, and elongation/ductility. A single lap joint was selected so that a TSS test could be used to assess the joint's mechanical condition. According to Saeed [14], the tensile shear load strength of welded materials was found to increase with peak welding current.

D. Optimization

This study considers three-level process parameters: welding time, welding current, and electrode force. Table 4 outlines these parameters at different levels. While orthogonal arrays simplify testing, they may overlook interactions between variables. Thus, only the main effect of each parameter on tensile strength was analyzed. To explore the entire parameter space, nine tests were conducted using the L9 orthogonal array.

Table 4. Process levels and parameters

Process Parameter	Level 2	Level 1	Level 3
Welding current (kA)	8	6	10
Welding time (cycles)	15	10	20
Electrode force (kN)	2.5	2.1	3.0

Furthermore, as producing strong weld joints is the aim of the endeavor, "higher is better" was selected as the quality attribute in this study. As a result, S/N ratios are calculated using the method below:

$$\left(\frac{sig}{noise}\right) ratio = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \qquad ((1))$$

Where n is the number of experimental trials and y_i is the response value of the ith experiment in the orthogonal array.

3 Results and Discussions

To investigate the Signal to Noise ratio, Minitab V17 was used. It is possible to discern between the effects of each welding parameter at different values on the Signal to Noise ratio since the investigative design is orthogonal. The tensile test findings for the nine distinct specimen trials are shown in Figure 2. Table 5 displays the maximum load and the extension at the maximum load, correspondingly. On the x-axis, the figure for the second specimen in the first experiment was located at a negative value. This results from the equipment not being reset before use. Though it has a similar extreme strength as the further data, the extreme strength data is still useful. As a result, it is accepted as genuine.

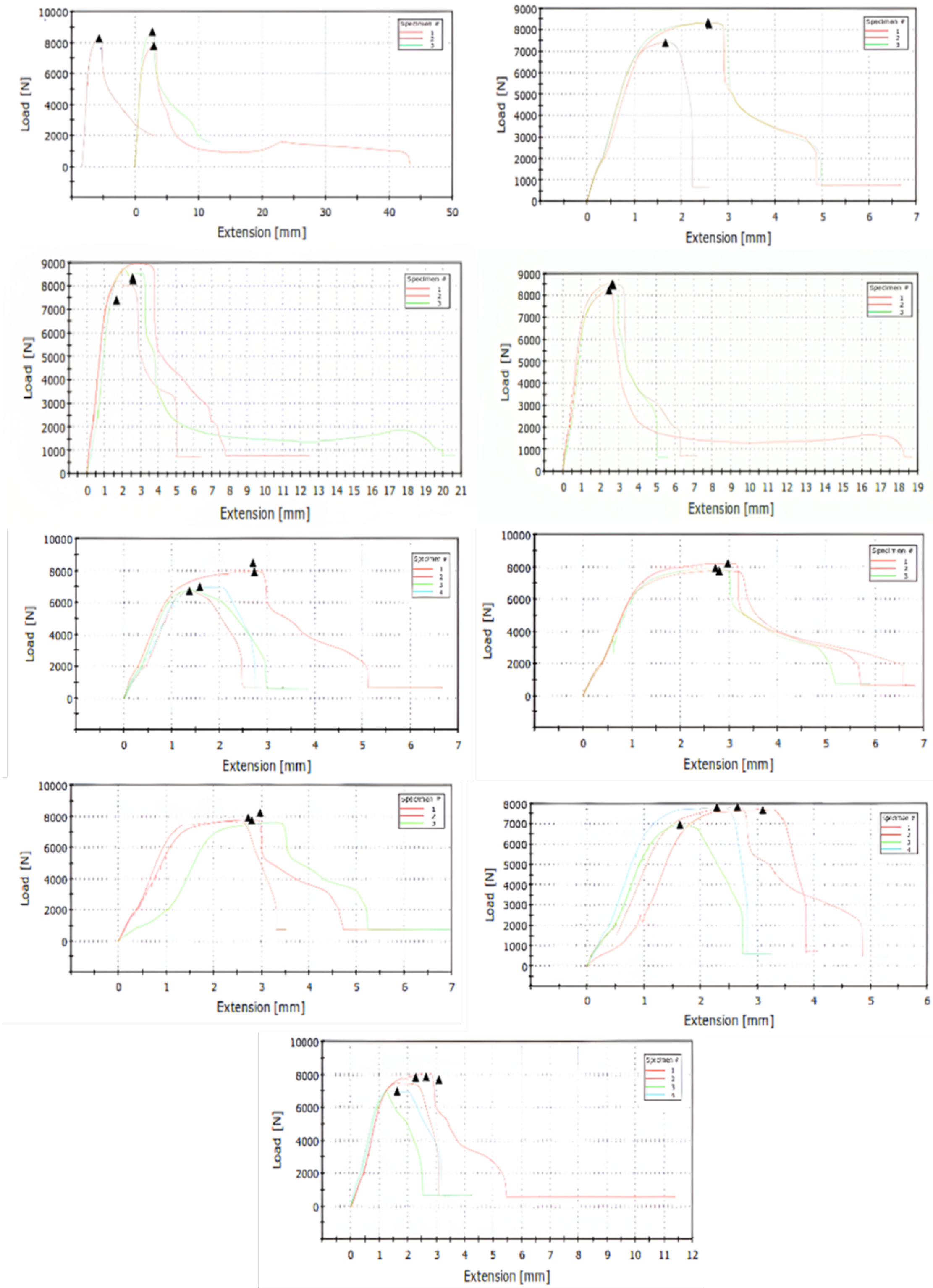

Fig 2. TSS test for specimen trails

Table 5. TSS test for trail

Trails for Tensile shear	Area (mm^2)	Maximum load (N)	Extension at maximum load (mm)
1	150.000	7898.75487	2.93721
	150.000	8364.87172	-5.67183
	150.000	8789.39954	2.75704
2	150.000	8475.57401	2.57602
	150.000	7509.13347	1.66278
	150.000	8271.45027	2.58641
3	150.000	8945.80168	3.01702
	150.000	8433.85766	1.75620
	150.000	8728.38883	2.15268
4	150.000	8260.25780	2.45720
	150.000	8540.14076	2.65275
	150.000	8566.19958	2.68847
5	150.000	7815.74252	2.73844
	150.000	6835.54856	1.37836
	150.000	6751.82388	1.35601
	150.000	6971.62061	1.58734
6	150.000	8230.30584	2.98276
	150.000	7756.47610	2.79606
	150.000	7820.75072	2.72847
7	150.000	7787.75409	2.75935
	150.000	7761.51857	2.35499
	150.000	7581.90817	3.24692
8	150.000	7683.39654	3.08250
	150.000	7855.63695	2.63700
	150.000	6975.88943	1.64265
	150.000	7716.50432	2.29251
9	150.000	8076.70750	2.78432
	150.000	7395.75676	1.68463
	150.000	6870.26344	1.24502
	150.000	7032.99414	1.36688

The experimental results of tensile shear strength (TSS) for each trial demonstrate that the TSS values range from 7.20 kN to 8.39 kN across the nine trials, with the highest TSS recorded for specimen 4 (8.39 kN) and the lowest for specimen 5 (7.20 kN). Each trial involved testing three to four specimens, with the average value used to represent the TSS for consistency and accuracy. In this investigation, TSS is considered a larger-the-better quality criterion for the welded specimens, as a higher TSS rating indicates greater joint strength and corresponds to a lower yield ratio. This approach ensures the identification of optimal welding parameters that enhance the mechanical performance of the welded joints. Table 6 displays the Signal-to-noise ratio results obtained by applying Equation ((1)).

In this work, finding the perfect resistance spot welding parameters involves a series of experiments using the Taguchi Method and Design of Experiments (DOE). First, the variables must be defined, and the response must be measured before using the DOE. Following the execution of each test parameter, a range of rates reflecting the desired effect of each input variable are defined and then this work examines the response for every run. Examining disparities between response readings from various input change groups is the evaluation strategy. Next, the input factors operating alone referred to as a single effect are blamed for these discrepancies.

Table 6 provides a summary of SNR for all levels. The ideal value is the one that balances the cost and quality of welding. Given the focus of this work, which focuses on TSS, the largest value represents the optimal value. The best value for every parameter is indicated by a star (*) in Table 7. Electrode force is the most significant metric in this work, as indicated by its ranking of number one.

Table 6. Results of SNR

Experiment number	SNR
1	18.27
4	18.53
3	18.72
2	18.05
6	18.01
8	17.61
5	17.01
9	17.33
7	17.72

Table 7. S/N response of the TSS

Parameter Level 1	S/N ratio			Rank
	Level 2	Level 3		
Welding time	18.19*	17.57	18.04	2
Electrode force	18.39*	17.84	17.56	1
Welding current	17.99*	17.96	17.83	3

The impact of various manipulation parameters on the signal-to-noise (S/N) ratio outcome, providing insight into their influence on tensile shear strength (TSS) which shows that electrode force has the highest S/N ratio at Level 1 (18.39), ranking it as the influential factor. Welding time follows, with its highest S/N ratio at Level 1 (18.19), placing it second in significance. Welding current, although slightly less impactful, records its highest S/N ratio at Level 1 (17.99), ranking third. The optimal levels for maximizing TSS, as indicated by the highest mean S/N ratios, are 2.1 kN for electrode force, 10 cycles for welding time, and 6 kA for welding current. Generally, specimens exhibit better quality and improved TSS with higher mean S/N ratio values, reinforcing the importance of carefully adjusting these parameters during the welding process.

An improved understanding of the relative importance of the various elements and characteristics that the analysis of variance (ANOVA) can examine is also given by the Taguchi approach. It is a statistical technique for quantitatively estimating the qualified significant aspects about quality attributes. If the p-value falls below the significance threshold, the factor is considered statistically significant. F-ratio or % contribution are common ways to express the relative importance of several elements. The greater the F-ratio, the more significant the impact of process parameter fluctuation on performance. Table 8 presents an ANOVA for parametric optimization of the S/N ratio in spot welding at a 95% confidence level.

If the probability value (p-value) of the factor is less than the significance level (α), then it is deemed statistically significant. A percentage contribution or an F-ratio are common ways to indicate the relative importance of factors. A lower p-value (less than 0.05) indicates a higher variable. An increased F-ratio suggests that the output is affected by variations in the system parameter. This method evaluated each welding parameter's significance by examining how the spot-welding parameters affected each outcome.

The larger the F value, the more significant the shift in the welding parameters' rank. The most significant factor influencing the results in this investigation is electrode force while welding current has less of an impact. This is because the lowest value is produced by welding current when compared to electrode force and welding time. Figure 3 displays the average signal-to-noise ratio.

Furthermore, a variable that contributes a high percentage will affect performance significantly even when it makes a tiny difference[15]. Electrode force, which accounts for 66.95% of the resistance spot welding parameter impact on the TSS, is the most significant factor. The fact that experimental errors only account for 0.3635 of the variances suggests that the experimental design was successful.

In this study, the ANOVA results for TSS reveal that Electrode Force is the most influential factor, contributing 66.95% to TSS, followed by Welding Time (25.77%) and Welding Current (7.28%). The Residual Error is minimal at 0.49%, indicating a robust model with high predictive accuracy. Comparatively,[16] presents similar findings, with Electrode Force contributing

Table 8. ANOVA results for TSS

Factors	Sum of squares	DoF	F	P	Mean of squares	Cont. (%)
Electrode force	50.813	2	130.432	0.005	25.4065	66.95
Welding current	5.825	2	14.15	0.023	2.9125	7.28
Welding time	17.776	2	54.35	0.035	8.888	25.77
Residual Error	0.3635	2			0.18175	
Total	74.7775	8				100

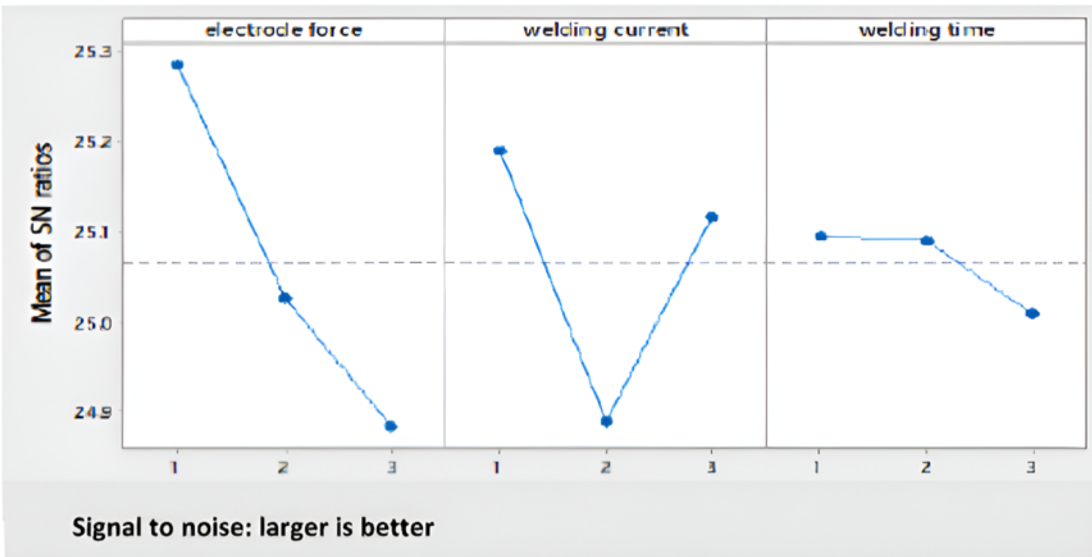

Fig 3. Mean of Signal to noise ratios

at 66.96%, Welding Time at 25.75%, and Welding Current at 7.29% closely aligning with this study's results. Their Residual Error also stands at 0.49%, further validating the consistency of both models. In contrast,[17] shows a significantly different distribution, with Welding Current dominating at 86.85%, while Welding Time contributes only 7.59%. The Residual Error is notably higher at 3.95%, suggesting a less reliable model with greater unexplained variance. The study's results stand out as the most balanced and reliable, with a strong emphasis on Electrode Force as the key determinant of TSS and a minimal Residual Error (0.49%), confirming the effectiveness of the selected model for optimizing spot-welding parameters in uncoated cold-rolled steel.

4 Conclusion

This study investigates the optimization and impact of welding parameters on the tensile shear strength of spot-welded uncoated cold-rolled sheets. ANOVA analysis reveals the significant influence of welding parameters on tensile shear strength. The generated response accurately predicts tensile shear strength, indicating a good fit. Optimal results are achieved with an electrode force of 2.1 kN, a welding current of 6 kA, and a welding time of 10 cycles. Electrode force emerges as a more crucial factor than welding time and current, as per ANOVA results. Consequently, the study concludes that Resistance Spot Welding parameters were effectively improved using the Taguchi method, enabling reasonable anticipation of jointed metals' tensile shear strength.

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