

Process Optimization of Spot Welding for Galvanized Automotive Steel Sheets

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Abstract

Resistance Spot Welding (RSW) is a pillar of the modern automotive industry with the usage of lightweight and high-strength products at the highest point of demand. The optimum weld quality of galvanized steel sheets which is a material of choice because of its additional corrosion protective property is however not achieved easily. This study is a well-developed data-based solution to designing the RSW process in the most efficient way, providing increased joint strength, structural soundness, and cost-effectiveness. An orthogonal array is used (L27) to perform a thorough experimental analysis of the impact of essential parameters such as the number of weld spots, the specimen and weld distance, the current, force, and the electrode using the SPSS program to determine the critical welding parameters. Knowledge of joints Using advanced mechanical testing such as tensile shear tests as well as cross-tension on precision-engineered fixtures gives definitive evaluations of how joints perform. Regression analysis is taken into use in order to come up with a good predictive model since the measured deviation between experimental and predicted tensile shear strength is low at 0.57%, which shows that the model is not erratic. In addition to the signal-to-noise ratio technique, the Taguchi approach to experimental design and analysis of variance (ANOVA) finds the optimal settings.

Keywords: Welding current, Quantity of spots, Distance between spots, Tensile and Shear strength, Taguchi method, Regression analysis, Optimization technique.

INTRODUCTION

The modern manufacturing landscape relies heavily on the efficiency and reliability of welding processes. Resistance spot welding has become a fundamental technique, particularly in the automotive sector. This study aims to unravel the complexities of resistance spot welding, with a specific emphasis on enhancing the tensile shear strength of welds. It focuses on galvanized steel sheets, selected for their strength and corrosion-resistant properties—crucial in the demanding conditions of the automotive environment. Over-welding, or the unnecessary application of excessive spot welds, increases production costs. Therefore, this study systematically explores both design and process parameters.

The number of spots, specimen thickness, spot spacing, electrode force, and welding current are scrutinized through carefully planned experiments. At the heart of the research is the diligent application of the Taguchi method, a reliable experimental design strategy. By calculating the signal-to-noise ratio (SNR) and employing analysis of variance (ANOVA), the study aims to uncover the intricate relationships between the aforementioned parameters and weld strength. The objective is clear: to optimize welding parameters to achieve enhanced tensile shear strength and cost-effectiveness in the production process. In manufacturing, resistance spot welding stands out as a cornerstone for assembling metal structures, particularly in industries like automotive, where

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structural integrity and efficiency are paramount. This research project focuses on predicting and optimizing the tensile shear strength of specimens by applying resistance spot welding techniques. While widely employed, spot welding presents several challenges and complexities. The problems of poor consistency in weld quality, weld spreading excess because of high current, and electrode contamination are raised in this study as critical issues to be conquered. The integrity and general competence of an integrated vehicle framework is largely pegged on the permanence of every spot weld. The numerous issues raised in the field require a thorough investigation that should determine the reasons of failure at different loading levels. The goal of this work is to select optimal values of various process variables in case of single-spot and multi-spot welds. It is aimed at having to achieve welds that not only attain the strength requirements but also aid production performance. At the center stage of this study is insight into how changing parameters in different loading levels influence the strength of spot weld. The study aims at improving design of spot weld joints so that structural integrity is achieved in a wide range of functions. The ultimate target is the eradication of the appearance of even a single defective welding, as the quality of welding is known to be one of the most important factors to guarantee the reliability of the end product. In the modern manufacturing plane, the aim of structural integrity is at times achieved in excess of necessity as spot welds by the welding companies frequently drop by the diligence of such companies to make such welds well above what is needful. Such a tendency on over-welding raises the production costs and points to the necessity of optimizing the usage of spot welds. The modelling and optimization of resistance spot welding is also a field of concern since manufacturing will continually move toward modifications. It is necessary to align the resistance spot weld performance metrics with several other process variables. The results of the current study are likely to produce a good contribution into this essential field of study that might be used to have quality data on how best process parameters should be set on a given work-piece. This will eventually assist in achieving welds of the demanded strength with minimum costs.

LITERATURE SURVEY

Eko Agustinus Budi Nusantara et al. [1] investigated spot welding of materials that are not compatible with each other, namely stainless steel and low-carbon steel. Research on how the welding current affects various weld material qualities is extensive. Welding current significantly affects nugget size and joint tensile-shear load capability, they discovered. Spot weld joints, which were made at the interface of two and more steel plates, have to be tested by their tensile strength and fatigue behavior. Similar studies were done by Vural et al. [2] on galvanized and austenitic stainless steels with the conclusion providing that fatigue strength was important in the ability of joints to react to different loading levels. Triyono et al [3] investigated the resistance spot welds of the AISI 304 austenitic stainless steel sheets in different thickness by studying their fatigue strength. Their results noted the existence of asymmetric weld nuggets, ripping fatigue fracture mechanism and an enhancement in the micro-hardness at the edge of the nugget due to large differences in the thicknesses. Using a cross-tension specimen, Doo-Hwan and Kim et al. [4] studied the fatigue life and tensile strength of cold-rolled mild steel as a function of welding factors such as current and duration. Weight and nugget sizes were used in tensile as well as fatigue tests. The authors observed that the J-integral parameter which involves both stress and equivalent stress intensity makes it easy to obtain the prediction of fatigue life in various specimen geometries, as compared to notching solutions.

A.M. Pereira et al. [5] investigated how different welding conditions affected the microstructure and tensile strength of spot welds in the aluminum 6082-T6 alloy. Hardness tests and microstructural analysis were used to determine weld quality. The fact that there was a higher failure load with prolonged time and more welding current on the static tensile shear test demonstrated this fact. Welding duration, current, and electrode force were investigated by M. Pouranvari et al. [6] for their potential effects on the mechanics and failure processes of low-carbon and dual-phase steels. Through the use of tensile shear testing, the failure mechanisms of interfacial and partial pullout could be determined. As the welding duration and current were increased, the electrode force was decreased, which facilitated the failure of the pull-out. The paper had highlighted that electrode expulsion and deep indentation should be avoided to realize the best pull out failure.

G. Mukhopadhyay et al. [7] fixed the serviceability of spot welds in reference to pre-strained and extra interstitial-free steel specimens. Greater pre-strain increased the strength of the weld but the substrate interface and heat-affected zone (HAZ) was the weakest point. Microstructural and hardness profiling showed that residual dislocation density rose with pre-strain, contributing to weld failure mechanisms. G. Mukhopadhyay et al. [8] The durability of spot welds in thin sheets of interstitial-free steels was further investigated by altering the nugget diameter, the methods of loading, and the alloy's chemical composition. Different nugget sizes were achieved by altering welding current. Various loading configurations—including sliding tension and pure shear—were tested. The results showed that weld strength remained constant for specific loading methods, and larger nuggets supported higher loads. Welded joints often exhibited greater strength than the base metal. V.J. Badheka et al. [9] selected 0.5 mm thick AISI 420 stainless steel (0.29% C) to assess weld cracking tendencies and failure modes. Mechanical peel tests indicated interface and nugget pull out failures. Nugget pull out was preferred, suggesting sufficient ductility and toughness. It is probable that the lack of post-heating, increased carbon content, and rapid cooling caused the nugget pull out and partial interfacial failures seen in the scanning electron microscopy (SEM) investigation. R.S. Florea et al. [10] studied fatigue behavior in resistance spot welding (RSW) of 6061-T6 aluminum. Weld nugget microstructures were analyzed under different welding parameters, including current, force, and after-heating duration. Iterative process optimization revealed that resistance patches significantly influence fatigue life and weld joint strength. P. Lardeur et al. [11] noted that early finite element (FE) models of spot welds lacked representation of actual weld size, stiffness, and force transmission, leading to significant prediction errors. Traditional meshing techniques required simultaneous meshing of both welded parts, complicating accurate simulation. S. Xu et al. [12] emphasized the need for simplified FE models in spot weld representation. As modeling each weld in detail is impractical, a unified approach allows reasonably accurate functional predictions across all welds.

M. Palmonella et al. [13] demonstrated that while coarse FE models of spot welds can be used for stiffness and noise-vibration-harshness (NVH) predictions, accurate fatigue analysis requires finer meshes for detailed local stress evaluation. Simplified models may therefore offer only approximate predictive performance during the early stages of vehicle design. A.G. Thakur et al. [14] presented a finite element analysis (FEA) of the RSW process that incorporated electrical, thermal, metallurgical, and mechanical phenomena. To study transient thermal behavior, they created a 2D axisymmetric model in ANSYS with the PLANE223 element for coupled-field analysis. The model provided insights into process mechanics and reduced the need for extensive weld parameter optimization. P.P. Kulkarni et al. [15] utilized Monte Carlo and Latin hypercube sampling to simulate single and multi-spot-welded specimens. Using a 3D nonlinear finite element model, they analyzed the uncertainty in the shear strength of multi-spot-welded lap-shear joints by examining variations in sheet thickness and nugget radius within feasible limits. The study computed failure probabilities to ensure weld reliability throughout a vehicle's lifespan. R.N. Raoelison et al. [16] focused on improving the accuracy of RSW simulations for zinc-coated sheets with rounded-tip electrodes. Their finite element analysis incorporated electric-thermal-metallurgical-mechanical (ETMM) parameters. The study highlighted the importance of accurately modeling the evolving contact radius and accounting for contact resistance—which varies with interface pressure and temperature—to simulate nugget growth effectively. C.L. Tsai et al. [17] developed a comprehensive FE model for the RSW process using grade ASS 347 stainless steel of both uniform and non-uniform thicknesses. The model, designed to account for rapid thermal cycles during welding, offered valuable insights into the thermal and structural responses of different material configurations under resistance spot welding.

Recent research by Rajalingam et al. [18] presented a comparative study of resistance spot and laser beam welding for ultra-high strength automotive steels, reporting improved joint performance for automotive applications. Bhuyan et al. [19] used a Taguchi approach to optimize spot welding parameters and significantly increased tensile shear strength in automotive steels. Effertz et al. [20] showcased machine learning-based optimization for refill friction stir spot welding in lightweight

aerospace alloys. Florea et al. [21] addressed fatigue, microstructure, and weld reliability in aluminum/steel, emphasizing optimization, durability, and defect reduction in modern spot welding. Recent studies have also integrated digital twins, online intelligent monitoring, and machine learning techniques for real-time defect detection and dissimilar material joining [22, 23]. They have also studied fatigue life and nugget microstructures under varying parameters in 6061-T6 aluminum spot welds. In summary, there is plenty of room for improving the weld strength of the resistance weld components.

In the context of a gap as mentioned above, the proposed research is focused on the following:

- Development of the mathematical model for resistance spot welding.
- Taguchi, response surface modelling, and linear regression with analysis of variance (ANOVA) for determining When doing resistance spot welding, the most crucial factor is Identifying optimal process parameters for resistance spot weld using Taguchi.
- Parametric optimization to optimize the process variables concerning resistance spot welding for improving weld strength.

PROPOSED SYSTEM

Methodology

The design of experiments encompasses a suitable selection of input factors and their levels. As per literature, based on pilot experimentation and testing machine specifications the parameters have been selected as welding current (A), work piece thickness in mm, electrode force (N), Distance between Spot Welds and spot number. An orthogonal array (L27) Taguchi design method has selected to determine optimum process parameters for spot welding process.

The methodology follows a systematic approach to comprehensively investigate and optimize resistance spot welding for both single-spot and multi-spot configurations. The research begins with a thorough theoretical study of the welding mechanism, followed by the selection of an appropriate workpiece configuration that aligns with the theoretical insights and facilitates practical experimentation. Loading conditions and process parameters are then carefully chosen through a series of well-reasoned experiments. The experimental phase involves performing resistance spot welding on the selected workpiece arrangement, including single-spot and multi-spot welds. Custom fixtures will be designed and fabricated to ensure highly reproducible and repeatable testing conditions for measuring weld strength. The experimental results will be rigorously analyzed, with a primary focus on the effects of process variables on the tensile and shear strength of the welds under various loading conditions.

Subsequently, a regression model would be proposed, incorporating process variables and workpiece properties to allow for a predictive evaluation of weld strength. In the final stage, the Taguchi method will be used to identify and optimize the process parameters for both single- and multi-spot welding. The ultimate goal is to enhance the durability of resistance spot welds, generating findings with significant implications for industrial practice.

Experimental procedure

The experimental setup utilized a Universal Testing Machine (UTM) to determine the weld strength of the spot-welded specimens. Initial process parameters, including welding current, electrode force, weld time, and radial spot spacing, were established. Based on these specifications, spot-welded samples with a thickness of up to 1.22 mm were carefully fabricated. Special fixtures, constructed from robust materials such as cast iron and mild steel, were designed to apply loads parallel to the weld seam on the specimens, ensuring consistent and repeatable testing conditions. Lap shear and cross-tension specimens were tested using the UTM, which was operated at a cross-head speed ranging from 1.32 mm/min to 2.0 mm/min to simulate dynamic loading situations. After testing, a Brinell microscope was used to measure the nugget diameter on specimens that experienced pullout failure. To ensure the accuracy and repeatability of the results, ten specimens were tested for each combination of welding

settings and loading conditions. The extensive data collected included weld strength, failure mode, and nugget diameter. This systematic experimental study provided valuable data on the dynamic response and strength characteristics of spot-welded joints under various conditions.

Proposed Design

Figure 1 shows the CAD Model of fixture and specimen. The system designed in relation to this study aims at systematically examining and optimizing resistance spot welding procedures by paying attention to spot-by-spot and multi-spot arrangement of the parts. The study, based on a well-formulated experimental method, commences by selection of materials, preparation of work piece, and pilot experimentation to outline the sweet spot of the welding parameters. The crux of the suggested system was to combine with Taguchi method in terms of experimental design, in which variables were pre-examined between welding current, electrode force, spot to spot spacing, the thickness of specimen and how many spots. To ensure symmetrical transmission of loads, design of fixtures is emphasized so as to provide precise and reliable conditions of testing.

The final step of the experiment is to carefully set up an electric resistance spot welding equipment according to the predictions' requirements. Testing statistics are derived using advanced geometry, and tensile shear testing is used to examine both multi-spot and single-spot welded specimens. The goal is to analyze the defining factors and their effects on spot weld strength in order to comprehend the subtle impact of the welding parameters.

This study aims to provide a comprehensive understanding of the complex processes governing resistance spot welding. By combining experimental precision, in-depth analysis, and advanced optimization methods, this work will develop predictive models and guidelines for improving weld quality. Ultimately, this systematic approach integrates rigorously controlled experiments with advanced analytical techniques to deepen the theoretical understanding of the process and establish practical guidelines for enhancing the reliability and productivity of spot welding methods. Figure 2 shows the pullout failure mode on the setup and Figure 3 shows the actual pullout failure in a spot weld. Figure 4 depicts the Electric Resistance Spot Welding Machine Setup on which experimentation has been conducted.

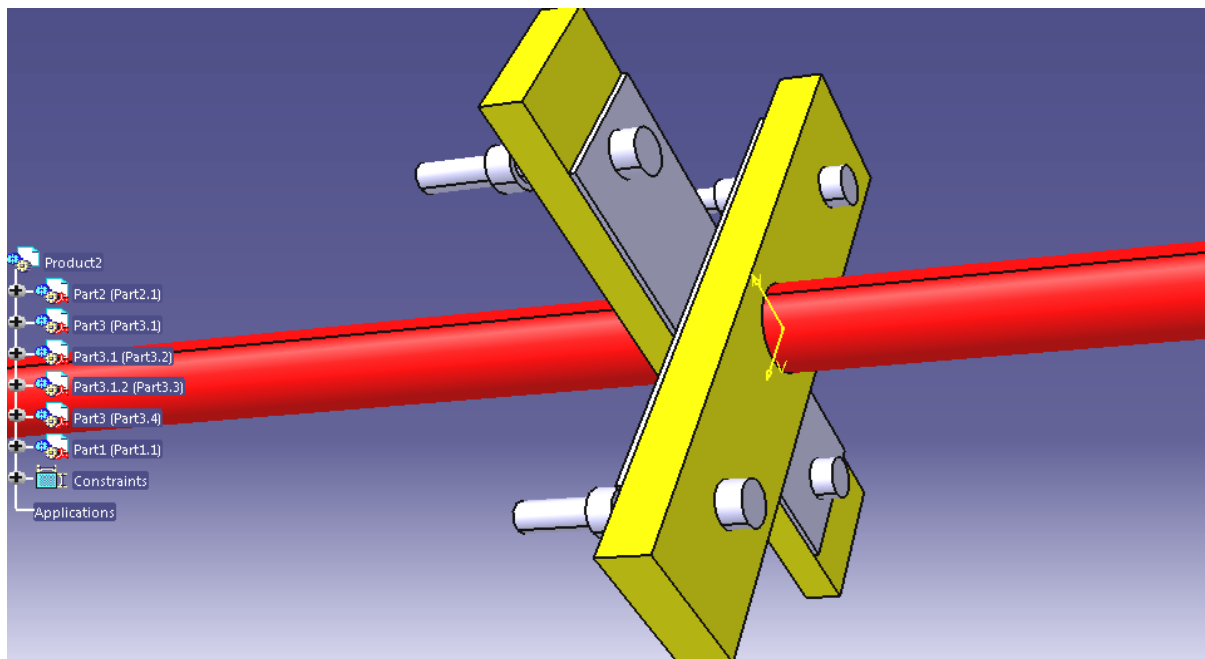


Figure 1. CAD model of fixture and specimen.

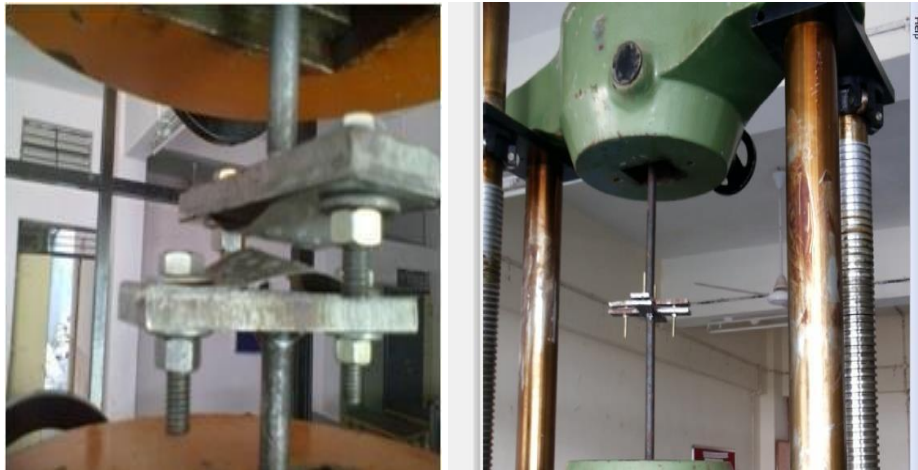


Figure 2. Pull out the failure mode.

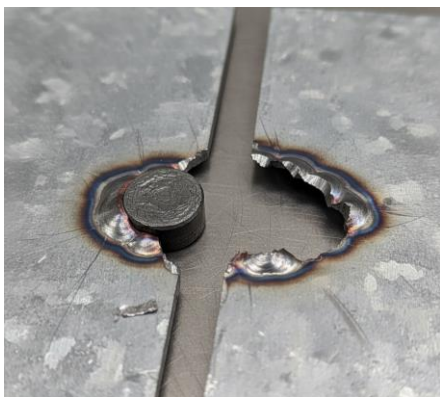


Figure 3. Actual pullout failure in a spot weld.



Figure 4. Electric resistance spot welding machine setup.

Table 1. Response for a signal-to-noise ratios.

Parameter Setting Level	Welding Current (A)	Workpiece Thickness (mm)	Applied Electrode Force (N)	Distance Between Spot Welds (mm)	Spot Number
1	25.50	32.0	34.56	32.07	30.02
2	37.3	33.90	31.4	34.10	34.10
3	37.24	35.85	33.97	33.93	35.45
Delta	11.96	3.14	3.32	2.05	4.98
Rank	1	3	4	5	2

Table 2. Tensile strength

Source	DF	Adj. SS	Adj. MS	F-Value	P-Value	% Contribution
A	2	24698.7	12349.2	21.85	0.0011	41%
B	2	4506.2	2251.1	3.97	0.062	8%
C	2	2912.8	1456.4	2.57	0.136	5%
D	2	2910.1	1453.9	2.56	0.138	5%
E	2	7962.1	3981.4	7.02	0.0169	13%
A*D	4	880.4	220.3	0.40	0.812	1%
A*E	4	11652.7	2914.2	5.14	0.0241	19%
Error	8	4525.5	575.8	-	-	-
Total	26	60055.2	-	-	-	-

S = 23.79, R-sq = 92.40%, R-sq (adj) = 75.52%

RESULTS AND DISCUSSION

Taguchi Analysis

Analysis of the signal-to-noise (S/N) ratio aims to identify optimal parameter levels by minimizing performance variation while moving the mean response toward a target value. In accordance with quality engineering principles, tensile strength is treated as a "larger-the-better" quality characteristic. The S/N ratio was examined for each level of the welding parameters, and the mean values were summarized using Minitab software. The main effects plot clearly illustrates the S/N ratio for each parameter. As the Taguchi analysis seeks to maximize the tensile strength output, the optimal parameter combination was identified as A2B3C1D2E3, based on the "larger-the-better" condition (Figures 5 and 6). The S/N ratio response, shown in Table 1, ranks welding current as the most influential factor.

Figure 5 illustrates the signal-to-noise (S/N) ratios for each input parameter at their respective levels. Based on this analysis, Figure 6 identifies the optimal parameter combination for maximizing the tensile strength of the cross-tension specimen. The predicted optimal settings are welding current at Level II, specimen thickness at Level III, electrode force at Level I, radial spot spacing at Level II, and number of spots at Level III.

Figure 6 also confirms these findings through an analysis of the mean response, which is consistent with the "larger-the-better" optimization criterion. Table 2 presents ANOVA results, revealing significant factors and their contributions. The F-test values, confidence levels, and percentage contributions are utilized. The fitness of experimental results, indicated by R² (92.46%) and R²_{adj} (75.50%), validates the model.

Notably, welding current significantly influences tensile strength, followed by the number of spots, specimen thickness, electrode force, and radial spot spacing in sequential order. The residual plots in Figure 7 confirm a strong agreement between the experimental and predicted results, indicating that the model's assumptions are satisfied. Finally, Figure 8 compares the predicted outcomes with the experimental data using a probability plot and histogram, further validating the model's accuracy.

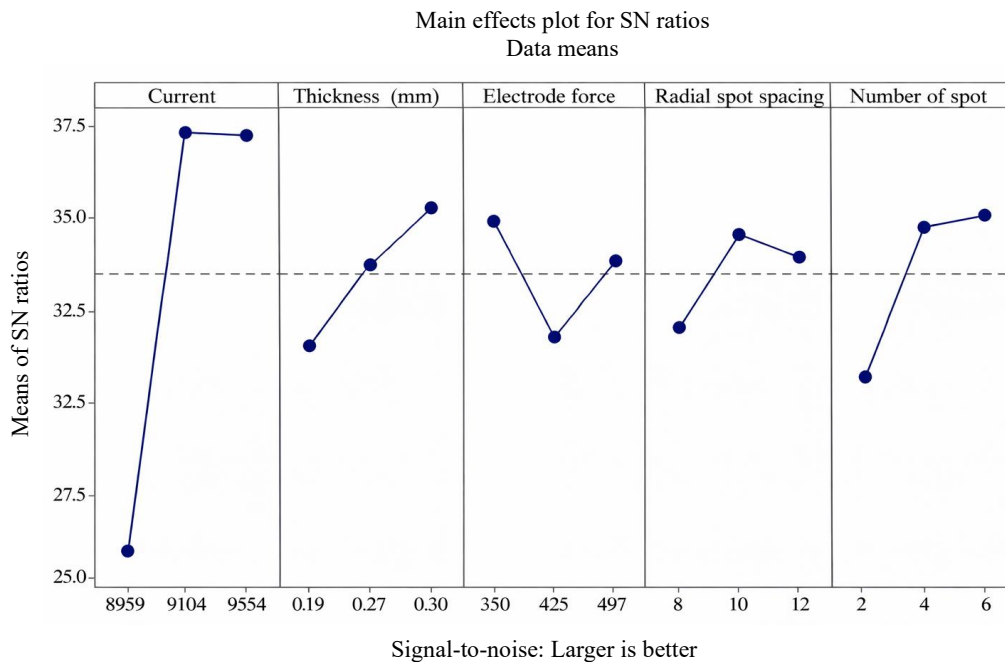


Figure 5. Variation of signal to noise ratio with respective input parameter and level.

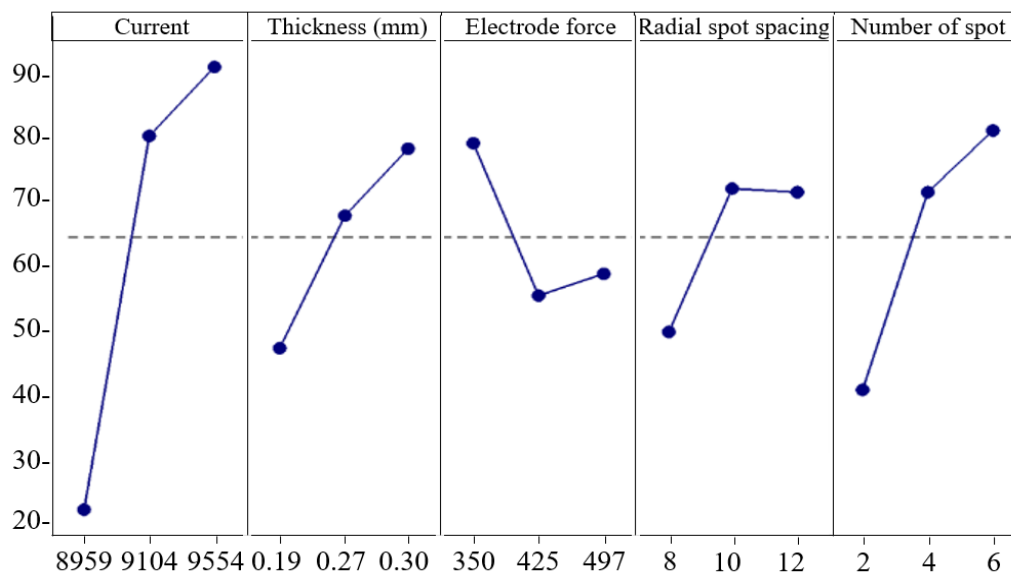


Figure 6. Variation of means with respective input parameter and level.

Regression modelling: A regression analysis has been performed on the experimental data. Modeling the tensile strength of cross-tension specimens that have been multi-spot welded is done using regression analysis. Tensile strength is measured on cross-tension specimens that have been spot-welded at random. The derived regression equation is presented below.

$$\text{Tensile Strength} = 3472 - 0.458 \times A - 10136 \times B + 5.96 \times C - 92 \times D - 526 \times E + (T S) \times 0.0049 \times A \times D + 0.0505 \times A \times E(1)$$

Where, ‘A’ represents the welding current (A), ‘B’ denotes the workpiece thickness (mm), ‘C’ indicates the applied electrode force (N), ‘D’ refers to the distance between spot welds (mm), and ‘E’ corresponds to the spot number.

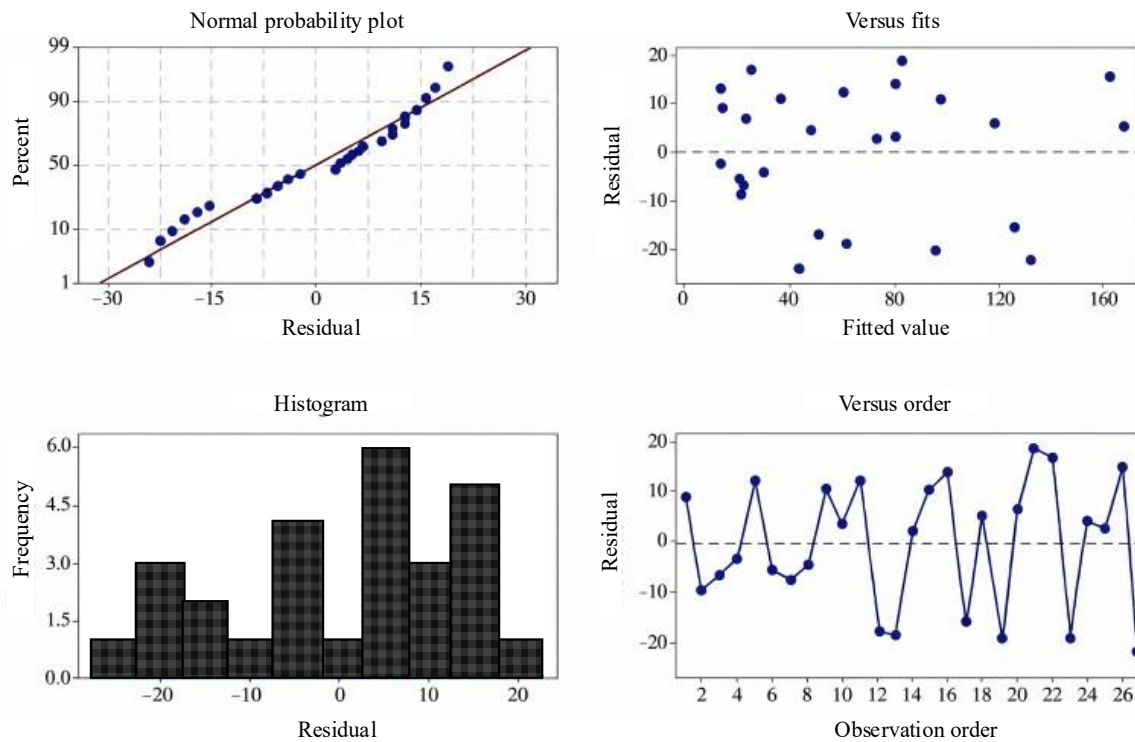


Figure 7. Residual plots for tensile strength.

Table 3. Validation for tensile strength.

Sr. No	Tensile strength (N)		Percentage Deviation
	X1	X2	
	<i>Regression Analysis</i>	<i>Experimentation</i>	
1	3436.45	3426.77	0.2648 %
2	3479.26	3450.12	0.8582 %
3	3522.95	3514.67	0.2509 %
4	3566.43	3546.59	0.5634 %

Confirmation tests were conducted to validate the derived regression equation. As shown in Table 3, the maximum deviation between the experimental results and the values predicted by the regression equation is only 0.85%, confirming that the model closely aligns with the experimental data.

To investigate the intricate dynamics of resistance spot welding, the interaction effect between two key parameters i.e. welding current and the number of spots, was meticulously examined. A contour plot was constructed to depict tensile strength variations as a function of these two variables while the other three welding parameters were held constant. Figure 8 illuminates the relationship between welding current, the number of spots, and their combined effect on tensile strength.

Figure 8 shows that the peak tensile strength is achieved at elevated welding current and a larger number of spots. As the current rises, the weld nugget diameter increases up to a critical value; beyond this point, excessive melting and expulsion reduce the nugget diameter, thereby diminishing tensile strength. Conversely, a lower tensile strength is observed at high current when fewer spots are used. Notably, a tensile strength exceeding 120 kgf is attained with six spots at 9,550 A. This contour plot was generated under constant conditions of an electrode force of 425 kgf, a specimen thickness of 0.27 mm, and a radial spot spacing of 10 mm. The interaction effects revealed by the plot provide useful guidance for selecting optimal parameter combinations and improving the efficacy of resistance spot welding.

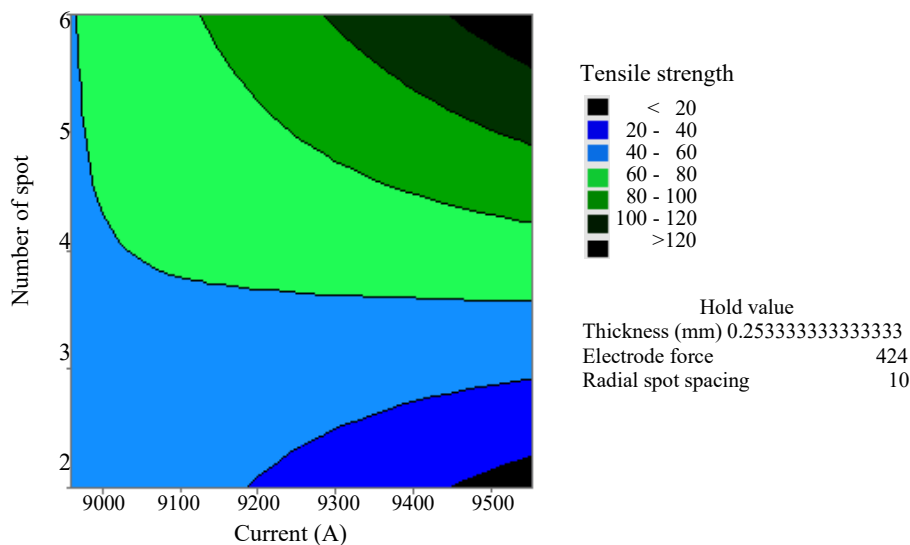


Figure 8. Plot illustrating the relationship between welding current and spot count.

Further Taguchi analysis and signal-to-noise ratios were used to evaluate the primary effects based on the experimental findings. ANOVA identified the factors that significantly influenced the response variables. A regression model was fitted to the experimental data to enable prediction, and tensile and shear strength results were extracted from the contour plot while examining various parameter combinations. The optimization and prediction results obtained using ANOVA are reported, and a confirmation test indicates that resistance spot welding parameters can be predicted and optimized with high precision using the established regression model.

CONCLUSION

The study is based on optimization of resistance spot welding in multi-spot designs by means of Taguchi-based experimentation. Such findings as the imperativeness of electrode force on indentation depth, the importance of welding current of value 10 KVA, and the positive effect of increment in weld time and tensile shear strength were discovered. The important combinations of key parameters in the tests of lap-shear and cross-tension specimens were discovered with the emphasis on the number of spots and the welding current. ANOVA confirmed the statistical fit of the experimental model, and confirmation tests showed strong agreement between experimental results and predictions from the regression equation, leading to significant improvements in lap-shear strength and cross-tension properties. This investigation provides valuable insights for improving the performance of multi-spot resistance welding. The proposed regression model can be used for real-time analysis of strain distribution, deformation, and transient thermal behavior. Future work could use the finite element method to investigate the effects of welding duration and cooling rate on weld strength. Further optimization strategies could also be used to compare the relative importance of various process parameters.

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