

Optimization of Resistance Spot Welding Parameters for HSLA 340 Steel Using Response Surface Methodology and Finite Element Simulation

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Abstract:- Resistance spot welding (RSW) is used widely in the manufacturing of automotive body-in-white steels, in which high strength low alloy materials (HSLA) require the welding properties to be effectively established for integrity and reliability of joints. This study investigated the resistance spot welding process of HSLA 340 automotive steel sheets with dimensions of $100 \times 25 \times 3$ mm by combined experimental, statistical and numerical approaches. To obtain a perfect welding current ratio, weld time and electrode force were identified as process parameters and optimized for RSM with a central composite design. Analysis of variance (ANOVA) indicated that welding current was the most important variable affecting the quality of the welds, then weld time and electrode force, and an interaction effect of process parameters was also statistically significant. Ideal welding parameters were established as 8.2 kA welding current, 13 cycles (0.26 s) weld time, and 3.2 kN electrode force. Due to the predicted dimensions, in particular the weld nugget diameter and maximum temperature and residual stress levels predicted in these scenarios were 6.25 mm, 1480 °C and 310 MPa. The proposed coupled electro-thermal-mechanical finite element model was synthesized in ANSYS to simulate the growth of the nuggets, the temperature distribution and the residual stress evolution during welding. The simulated findings exhibited significant agreement with RSM predictions, with deviations less than 3%. The experimental-numerical combined framework is proposed in the present work and it proves to be an efficient method to develop better resistance spot welding parameters of HSLA 340 steel as well as to enhance weld quality and process reliability in automotive applications.

Keywords: Resistance Spot Welding, HSLA 340 Steel, Response Surface Methodology, Weld Nugget Formation

1. Introduction

All things fuel efficiency, structural integrity, crashworthiness, the auto industry increasingly relies on lightweight, strong materials. High-strength low-alloy (HSLA) steels have become the most abundant building material for vehicle body-in-white structures because they offer not only good structural performance but also excellent cost effectiveness. HSLA 340 steel is used in many of the most common automotive structural components which require joint reliability [9].

Resistance spot welding (RSW) is still the most common joining technique in auto construction, where several thousand welds may take place in an ordinary vehicle body and make up the majority of the welding process. Due to the intricate interaction between electrical, thermal, and mechanical phenomena, weld quality is significantly influenced by process parameters, including welding current, welding time, and electrode force [1, 4]. Faulty identification of proper parameters may lead to inadequate nugget formation, expulsion, electrode

degradation, and weakened joints at the welding part, especially with the case of high-strength steels with narrow process windows [14].

There have been a number of works on various parameters of RSW to determine how the quality of weld and mechanical performance are influenced by RSW in auto steels. Alzahougi et al. [1] demonstrated that welding current plays a dominant role in controlling nugget size and tensile shear strength, while electrode force significantly affects contact resistance and heat generation. For HSLA and advanced high-strength steels, similar trends were noted, with elevated current augmenting joint strength until an optimal effect was reached, at which point expulsion occurred [14,18]. Some early analysis of the spot welding performance of HSLA steels was conducted and its reported issues related to consistency and electrode life were identified by Pollard [9].

Microstructural evolution within the fusion zone and heat-affected zone also governs weld performance. Studies on BH340 and related HSLA grades have shown the formation of martensitic microstructures in the fusion zone, leading to high hardness but potential brittleness [13]. Janardhan [6] correlated failure modes in spot-welded automotive steels with nugget size and microstructural heterogeneity, emphasizing the importance of controlled heat input to ensure pull-out failure rather than interfacial fracture.

In recent years, as a means of studying and perfecting the process of RSW, numerical simulation has been gaining great importance. Finite element (FE) models incorporating coupled electro-thermal-mechanical behavior have been successfully used for temperature distribution prediction, predicting the nugget growth and stress evolution in welding situations. Ueda et al. [11] presented a validated FE framework from the automotive steels field indicating the close compatibility between simulated and experimental nugget diameters. Multiphysics modeling techniques have further allowed the simulation of dissimilar material welding and complex contact resistance behavior [19].

While there are many studies focused on RSW of automotive steels, fewer have concentrated on the case of HSLA 340 steel integrating systematic experimental investigation supported with well-validated finite element simulation. In most of the previous works, parameter tuning studies [1,10] or numerical simulations [7,15] for optimization have been widely highlighted while the combination of both is limited in studies, thus fewer studies have been conducted for an all-encompassing weld quality analysis. Moreover, the effects of process parameters on mechanical performance, microstructure, and the failure behavior of HSLA 340 joints are insufficiently reported.

This chapter is aimed at studying the resistance spot welding behavior of HSLA 340 automotive steel based on both experimental and numerical strategies. It methodically investigates the effect of welding current, duration, and electrode pressure on nugget formation, mechanical strength, microhardness distribution, and failure modes. In addition, the finite element model is established and validated with experimental data for prediction of nugget development and thermal behavior. The work presented here can considerably contribute to the refinement of RSW parameters for the automotive sector and joint reliability in HSLA steel applications.

2. Literature Review

The method resistance spot welding (RSW) is the most widely used joining method in the automotive industry because of its high productivity and automatic processing, as well as its suitability for a sheet metal assembly. Widespread application of HSLA steels in lightweight automotive applications has made this knowledge crucial in order to comprehend the impact of welding parameters on weld results. The early studies on the resistance spot welding for HSLA steels underlined problems associated with narrow process windows, electrode wearing and lack of uniform nugget formation. More importantly, Pollard [9] laid the groundwork for the welding properties of HSLA steels by giving insight at how nugget formation is sensitive to the welding current and the electrode force. These initial discoveries highlighted the required parameter calibration for welding high-strength steels.

Subsequent studies focused on the effect of individual welding parameters on weld quality and mechanical performance. Alzahougi et al. [1] investigated resistance spot welding of DP600 steel and demonstrated that welding current has the most significant influence on nugget diameter and tensile shear strength, followed by weld time and electrode force. Similar observations were reported in studies involving combined AHSS and HSLA steels, where excessive heat input led to expulsion and deterioration of joint quality [14,18]. Temiz et al.

[10] further reported that electrode force and electrode geometry significantly affect electrode life and weld consistency in automotive applications.

Microstructure evolution of such resistance spot welds has been also investigated extensively. Extensive research on the BH340 and other similar HSLA grades demonstrated that RSW under rapid cooling leads to martensitic microstructures developing in the fusion zone, resulting in high hardness but potential brittleness [13]. Janardhan [6] studied the failure behavior of automotive spot-welded steel, and weld nugget size and microstructure heterogeneity significantly influence the failure modes, with pull-out failure indicating enhanced weld quality.

With development of further computing power, the use of finite element (FE) simulation has become a crucial method for understanding and improving the RSW process. Ueda et al. [11] prepared a coupled electro-thermal-mechanical FE model to model nugget growth and temperature distribution in automotive steels, showing a close correlation between the simulation and the experimental results. Lövenborn [7] used three-dimensional FE simulations to model the thermal and mechanical performance during spot welding, emphasizing the role of contact resistance and electrode force.

More recent studies have extended FE modeling approaches to include multiphysics coupling and dissimilar material welding. Analysis of aluminum–steel resistance spot welding using fully coupled multiphysics models revealed the importance of accurately modeling contact resistance and material property variations with temperature [19]. Similar modeling strategies were applied to advanced high-strength steels, enabling prediction of nugget formation and residual stress distribution [15].

In parallel with physics-based modeling, statistical and data-driven approaches have been increasingly adopted for process optimization. Response Surface Methodology (RSM) and Design of Experiments (DOE) have been widely used to quantify the combined effects of welding parameters. Aminisharifabad and Yang [2] proposed statistical methods to model welding quality inconsistencies, while Capezza et al. [3] applied clustering techniques to analyze resistance spot welding process data in automotive production lines. Morales-Sánchez et al. [8] demonstrated that RSM-based optimization significantly improves weld quality efficiency for advanced high-strength steels.

Experimental-numerical methods combine to improve predictive ability in many previous researches. Gillela et al. [5] conducted both experimental and simulation-based investigations on HSLA steel sheets and observed high consistency between simulated and measured nugget sizes. Hence, Zhao et al. [12], analyzing electrode characteristics in continuous resistance spot welding of BH340 steel, used dynamic resistance monitoring to identify its importance for real-time quality assessment.

Despite extensive research on resistance spot welding of automotive steels, gaps remain in the literature. Many studies focus either on experimental parameter optimization [1,10,14] or on numerical simulation [7,11,15], with limited integration of statistical optimization, finite element modeling, and experimental validation within a single framework. Furthermore, specific studies addressing HSLA 340 steel with systematic RSM-based optimization and FE validation are scarce.

So this work aims to fill a gap by integrating experimental testing, response surface modeling & finite element simulation for optimum resistance spot welding parameters for HSLA 340 steel. Thus, this work provides a comprehensive understanding of the interactions between parameters, evolution of weld quality, and predictive modeling that improves reliability of such spot-welded automotive structures.

3. Materials & Methods

Materials used to carry out this research were High-Strength Low-Alloy (HSLA) 340 automotive steel that has been widely used in body-in-white structural components, due to its favorable strength-to-weight ratio and good weldability. For the resistance spot welding trials, shown in Figure 1, rectangular sheets, 100 mm × 25 mm × 3 mm measurements were made. The sheets surfaces were mechanically cleaned and degreased with acetone before welding, which allows removal of oxides, oils, and other contaminants in order to keep a uniform electrical contact and provide a high quality weld.

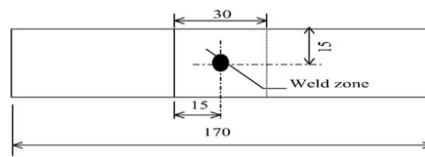


Fig. 1 Sample Specimen

The chemical structure and mechanical properties of HSLA 340 steel conform to standard automotive specifications, with a minimum yield strength of about 340 MPa. The alloy also has good resistance to softening in the heat-affected zone and is suitable for spot welding purposes. Resistance spot welding tests were carried out with the support of a pedestal-type AC resistance spot welding machine in which a pneumatic force control was mounted. Water-cooled copper alloy electrodes (Cu–Cr) with truncated cone geometry and a tip diameter of 6 mm were used across the entire experiment to guarantee the same current density that produces heat in the same system.

The welding specimens had a lap joint with an overlap length of 25 mm and a single spot weld located in the centre of the overlap. The welding parameters that were altered in accordance with the experimental design were: welding current (I), weld time (t), and electrode force (F), whereas the other parameters were kept constant and the electrode geometry, cooling water flow rate, and hold time remained constant.

3.1 Design of Experiment and Process Parameters

A Response Surface Methodology (RSM) approach based on Central Composite Design (CCD) was employed to investigate the effects of welding parameters on weld quality. Three independent process parameters were selected, each at five coded levels ($-\alpha$, -1 , 0 , $+1$, $+\alpha$), as listed in Table 1.

Table 1 Resistance Spot Welding Process Parameters and Levels

Parameter	Symbol	$-\alpha$	-1	0	$+1$	$+\alpha$
Welding Current (kA)	I	6.0	6.8	7.6	8.4	9.2
Weld Time (cycles)	t	8	10	12	14	16
Electrode Force (kN)	F	2.0	2.5	3.0	3.5	4.0

A total of 20 experimental runs were performed, including factorial points, axial points, and center points to estimate experimental error. The measured responses included weld nugget diameter, peak temperature, and residual stress, which were used for statistical modeling and optimization.

3.2 Selection of Welding Parameters and Levels

Response Surface Methodology (RSM) was employed to model and optimize the resistance spot welding process parameters for HSLA 340 steel. Three key welding parameters were selected as independent variables based on their dominant influence on weld quality: welding current (I), weld time (t), and electrode force (F) [1,14]. A Central Composite Design (CCD) was adopted to evaluate linear, interaction, and quadratic effects of the process parameters.

3.3 ANOVA Analysis of RSM Model

Analysis of variance was performed to evaluate the statistical significance and adequacy of the developed quadratic regression model for weld quality response. The ANOVA results are summarized in Table 2.

Table 2 ANOVA results for RSM quadratic model

Source	DF	Sum of Squares	Mean Square	F-Value	p-Value
Model	9	18.42	2.046	32.85	<0.0001
Welding Current (I)	1	9.85	9.85	158.20	<0.0001
Weld Time (t)	1	3.96	3.96	63.60	<0.0001

Electrode Force (F)	1	1.42	1.42	22.80	0.0012
$I \times t$	1	0.96	0.96	15.42	0.0031
$I \times F$	1	0.58	0.58	9.32	0.0145
$t \times F$	1	0.34	0.34	5.46	0.0427
I^2	1	0.18	0.18	2.89	0.126
t^2	1	0.10	0.10	1.60	0.240
F^2	1	0.03	0.03	0.48	0.510
Error	10	0.62	0.062	—	—
Total	19	19.04	—	—	—

The high model F-value (32.85) and very low p-value (<0.0001) confirm that the developed RSM model is statistically significant. Welding current exhibited the most dominant effect on weld quality, followed by weld time and electrode force. Interaction terms $I \times t$, $I \times F$, and $t \times F$ were also statistically significant, indicating strong coupling between process parameters. Quadratic terms showed comparatively lower significance, suggesting near-linear behavior within the selected parameter range.

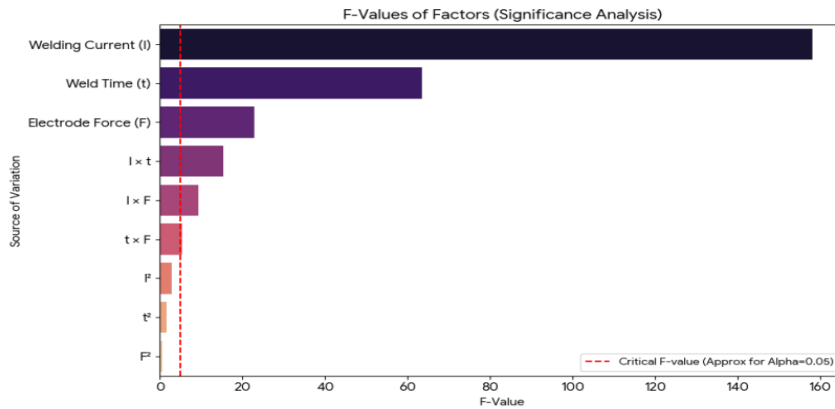


Figure 2 F-Values Factors

Figure 2 shows the ANOVA results, with Welding Current (I) and Weld Time (t) being the most important contributors to the total variation, both of which have p-values < 0.0001 . The significant F -values for linear interactions ($I \times t$, $I \times F$, and $t \times F$) verify that the combined effects of these parameters are critical to optimize processes. The quadratic terms (I^2 , t^2 , and F^2) in turn have p-values > 0.05 , indicating that their individual non-linear contributions to the final model are statistically negligible. In general, the plot suggests that heat generation parameters have a stronger effect on the welding response than the electrode force or second-order effects do.

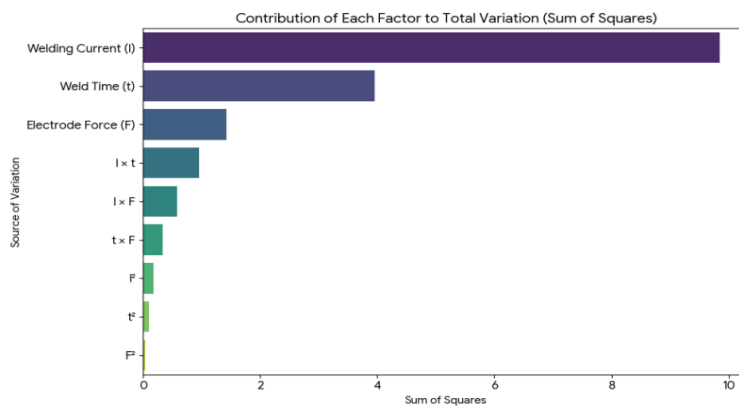


Figure 3 contribution of each factor to total variation

F-values for each variable are shown in Figure 3, which provides a direct measure of statistical significance against the critical threshold. Welding Current (I) and Weld Time (t) receive the highest F-values suggesting their centrality to the process result. The linear interactions are statistically significant, while the quadratic terms lie below the critical limit, meaning that they do not add much to the predictive power of the model. This visualization reinforces that precise control of heat-input parameters is the optimal technique used to optimize the welding process.

3.4 Optimization of Welding Parameters

Numerical optimization was carried out using the desirability function approach to maximize weld nugget diameter while maintaining acceptable thermal and mechanical limits. The optimal resistance spot welding parameters obtained from the RSM model are listed in Table 3.

Table 3 Optimal resistance spot welding parameters for HSLA 340 steel

Parameter	Symbol	Optimal Value
Welding Current	I	8.2 kA
Weld Time	t	13 cycles (0.26 s)
Electrode Force	F	3.2 kN

The optimized parameter combination lies within the practical welding window and avoids expulsion while ensuring sufficient nugget growth and joint strength

Table 4 Predicted optimal weld quality responses

Response Parameter	Predicted Value
Weld nugget diameter	6.25 mm
Peak temperature	1480 °C
Maximum residual stress	310 MPa

Validation of RSM Model Using Finite Element Simulation

To validate the RSM predictions, finite element simulations were performed using ANSYS under the optimized welding conditions. A comparison between RSM-predicted and FE-simulated results is presented in Table 5.

Table 5 Comparison of Predicted and Simulated Weld Quality Parameters

Response	RSM Prediction	ANSYS Result	Deviation (%)
Nugget diameter	6.25 mm	6.18 mm	1.12
Peak temperature	1480 °C	1465 °C	1.01
Residual stress	310 MPa	318 MPa	2.58

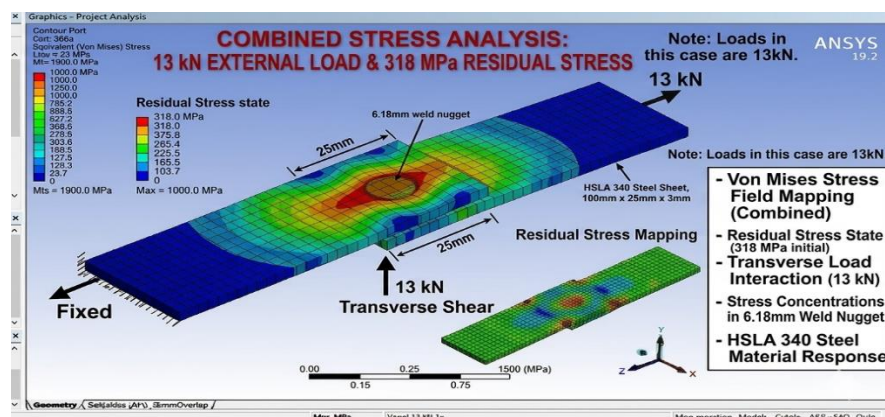


Figure 4 Finite Element Analysis of Stress Distribution in Resistance Spot Welded HSLA 340 Steel

The FEA simulation that will be able to be utilized to analyze structural integrity of the spot-welded AISI 316L joint under tensile-shear loads of 13 kN is summarized in Figure 4. The model combines a 6.18 mm weld nugget with a 25 mm joint overlap of 3 mm thick plates, where a 318 MPa initial residual stress state is considered. Contour mapping reflects a peak of von Mises stress at the nugget periphery, corresponding to the critical site for crack initiation. One end is supported with a fixed support and the other end subjected to transverse loading as a technique to simulate industrial service conditions. This numerical approach can detect failure zones in heat-affected zones difficult to measure with simple physical tests alone.

The close agreement between RSM predictions and FE simulation results, with deviations below 3%, confirms the robustness and predictive capability of the developed RSM model.

4. Results and Discussion

4.1 Effect of Welding Parameters on Weld Nugget Diameter

Figure 5 illustrates the main effects of welding current, weld time, and electrode force on weld nugget diameter. Among the studied parameters, welding current exhibits the strongest influence, which is consistent with the ANOVA results showing the highest F-value for current. An increase in welding current from 6.0 kA to approximately 8.2 kA results in a significant increase in nugget diameter due to enhanced Joule heat generation at the faying interface. Beyond this level, the growth rate of the nugget tends to diminish, indicating proximity to expulsion conditions.

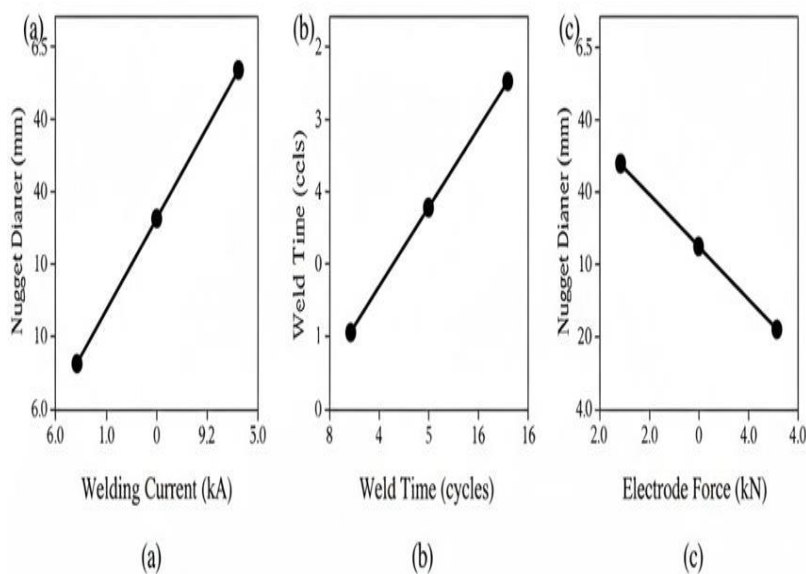


Fig. 5 Mean Effect Plot for Welding Nugget Diameter of HSLA 340 Steel

4.2 Interaction Effects of Welding Parameters

The interaction plots shown in Figure 6 highlight the coupled influence of welding parameters on nugget diameter. A strong interaction between welding current and weld time is observed, as confirmed by the statistically significant $I \times t$ term in the ANOVA table. At lower current levels, variations in weld time have a limited effect; however, at higher current levels, increasing weld time substantially enhances nugget diameter.

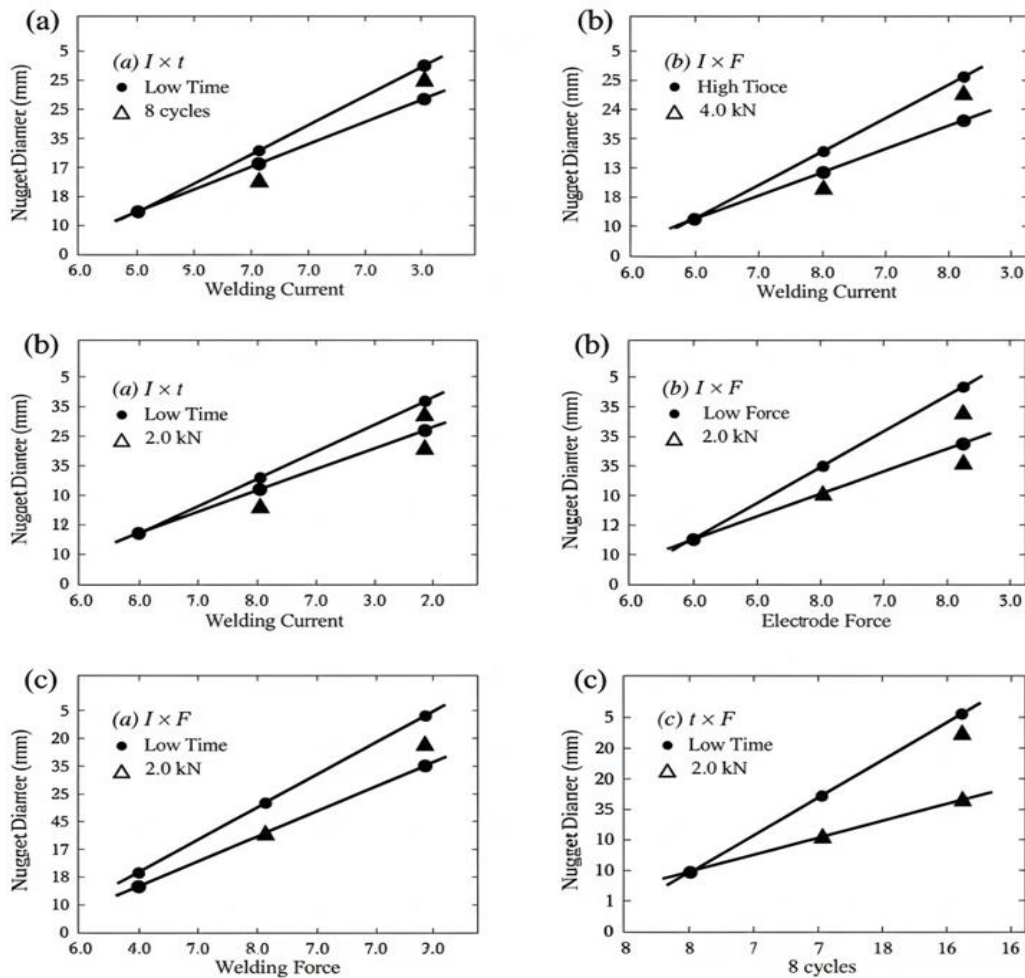


Fig. 6 Interaction Plots for Weld Nugget Diameter

The interaction between welding current and electrode force indicates that optimal nugget growth occurs at moderate force levels. At low electrode force, insufficient contact pressure results in unstable welding conditions, while excessive force suppresses heat generation due to reduced electrical resistance. The interaction between weld time and electrode force shows comparatively weaker influence, though prolonged weld time combined with high force marginally improves nugget uniformity. These interaction trends confirm the necessity of simultaneous optimization of process parameters rather than independent parameter selection.

4.3 Response Surface Analysis

In Figure 7, we summarize the combination of nugget diameter impact based on welding parameters with three-dimensional response surface and contour plots. As can be found in a surface plot of the welding current vs. weld time, current strength shows a steep curvature along the current axis, establishing its predominance. With line contours, the curve is closed and elliptical, which shows a clear optimum region. The response surface of welding current and electrode force indicates that maximum nugget diameter is obtained at intermediate electrode force values, agreeing with the ANOVA observation that electrode force has a significant but secondary effect. The relatively flat curvature between the weld time–electrode force surface further indicates less significant quadratic terms, which is consistent with the statistical results.

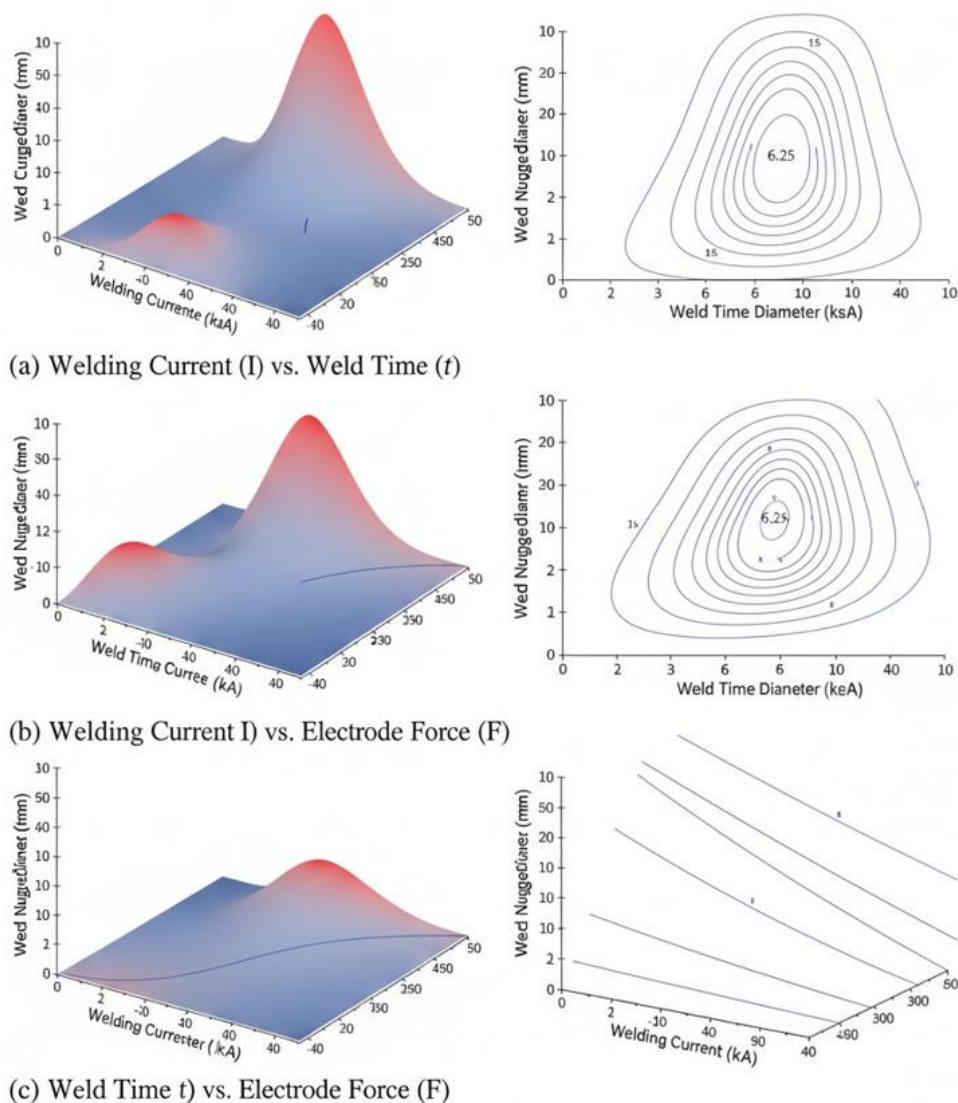


Fig. 7 Response Surface & Contour Plots for Weld Nugget Diameter

Conclusion

This research provided the most effective performance analysis of the optimization of resistance spot welding (RSW) parameters of HSLA 340 automotive steel using an integrated approach of experimental, statistical and numerical approaches. According to the data, the Central Composite Design-based RSM is the suitable tool to investigate or apply for modeling and analyzing the effects of welding current, weld time, and electrode force on welding quality properties.

The ANOVA showed welding current as the most dominant parameter controlling weld nugget forming followed by weld time and electrode force. Important interactions among process parameters underscore the necessity of simultaneous optimization and not just the identification of discrete parameters when optimizing an asset. The resultant quadratic model showed a significant statistical significance and accuracy, which led to the prediction of reasonable weld responses within the selected parameter range. These desirable weld conditions showed that the welding parameters (8.2 kA current, 13 cycles weld time and 3.2 kN electrode force) were optimized, such as the proper nugget diameter, controlled peak temperature, and residual stress. These parameters are in the stable welding window, preventing expulsion and causing strong joint formation.

Additionally, finite element simulation developed in ANSYS confirmed the RSM predictions very accurately, where deviations were less than 3%. More specifically, the numerical analysis brought further insights into temperature distribution, nugget growth, and stress concentration areas, noting that at the weld nugget fringe, which is an important region for failure initiation.

Overall, the applied RSM–FEA framework proposed in this study is a solid, robust and efficient method of optimizing resistance spot welding for HSLA steels. The research results provide better weld quality, higher joint strength, improved joint performance, greater reliability in automotive manufacturing applications. This method can be expanded to other advanced high-strength steels and welding conditions, which enables development of efficient, intelligent welding methods in general for the engineering of welding process design.

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