Optimization of Resistance Spot Welding Parameters for 316L Stainless Steel Using Response Surface Methodology and Box-Behnken Design: Investigation on Joint Characteristics and Performance

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Abstract:- Resistance spot welding (RSW) is a commonly utilized method for the fusion of metals in diverse sectors such as automotive, aerospace, and manufacturing. The present study aims to examine the significant impact of process parameters in the Resistance Spot Welding (RSW) technique on the properties and effectiveness of joints created in sheets of 316L stainless steel. 316L stainless steel is widely recognized for its exceptional resistance to corrosion and impressive mechanical qualities, rendering it a highly favoured material for applications that require utmost reliability and performance. The study commences by investigating the impact of crucial resistance spot welding (RSW) process parameters, including welding current, welding time, and electrode force, on the properties of the joint. A comprehensive parametric investigation is undertaken to get insight into the influence of parameter variations on the microstructure, nugget size, and heat-affected zone (HAZ) of the welded joints. The significance of welding current is particularly highlighted, with an emphasis on its function in regulating the size of the weld nugget and the subsequent strength of the connection. The evaluation of mechanical performance plays a crucial role in understanding the effectiveness of welded joints. This study aims to provide a comprehensive analysis of the tensile strength, shear strength, and fatigue parameters of resistance spot welded (RSW) joints. This study examines the impact of process parameters on the mechanical properties of joints, aiming to get a deeper understanding of the ideal circumstances necessary to achieve welds with superior strength and durability. In addition, the microstructural analysis elucidates the relationship between the welding parameters and the grain structure present in the joint region. Comprehending these microstructural alterations is vital in order to forecast and regulate the mechanical characteristics of the weldments. The results of this study hold significant importance for industries and applications that heavily depend on 316L stainless steel. They offer a comprehensive guide for enhancing resistance spot welding (RSW) procedures in order to achieve enhanced joint properties and overall performance. The findings derived from this study have the potential to contribute to the improvement of the dependability and durability of welded elements in high-stakes settings. This work makes a valuable contribution to the continuous endeavours aimed at enhancing the quality and efficiency of resistance spot welding (RSW) in 316L stainless steel applications by elucidating the complex correlation between welding parameters and joint quality.

Keywords: Resistance Spot Welding, 316L Stainless Steel, Process Parameters, Joint Characteristics, Mechanical Performance, Microstructure, Optimization

1. Introduction

Resistance Spot Welding (RSW) is a prevalent and widely used method of welding metallic materials in several industries. It is highly regarded for its effectiveness and efficiency in generating durable bindings. Nevertheless, since various sectors undergo transformations and require welded joints to exhibit higher levels of performance and reliability, there exists a significant urgency to conduct comprehensive examinations of the Resistance Spot Welding (RSW) procedure. Recent research efforts have not only emphasized the importance of this requirement but have also aimed to enhance RSW by investigating its parametric effects, in order to maintain its effectiveness and efficiency as a joining technique. The necessity for further research in the realm of RSW is emphasized by a succession of recent scholarly inquiries. Ding et al. [04] highlighted the need of optimizing resistance spot welding (RSW) procedures for materials with high strength, with the objective of improving the mechanical characteristics of welded joints [04]. Chen et al. [05] emphasized the significance of investigating welding parameters and their impact on the strength of joints, particularly when dealing with dissimilar materials [05].

Furthermore, research on RSW (Resistance Spot Welding) has expanded beyond traditional methods. In their study, Rajak et al. [06] presented a new TIG-spot welding methodology and conducted a comparative analysis with the conventional RSW method. This investigation highlights the increasing attention towards different welding approaches and their associations with processing, microstructural characteristics, and mechanical properties [06]. In their study, Asati et al. [07] undertook a comparative analysis to assess the appropriateness of self-piercing riveting (SPR) as a connecting method for automotive-grade dissimilar galvanized steel sheets, in comparison to resistance spot welding (RSW). The present work emphasizes the necessity of investigating alternate methods of joining in order to maximize resistance spot welding (RSW) in diverse applications [07]. Failures within the realm of resistance spot welding (RSW) techniques are a matter of considerable concern. The study conducted by Tolton et al. [08] examined instances of failure in resistance spot welds within custom hot stamped assemblies. The research highlighted the significant significance of comprehending and mitigating failure modes in order to enhance the efficiency of resistance spot welding [08]. Furthermore, the optimization of resistance spot welding (RSW) is closely interconnected with the manipulation of welding parameters. The study conducted by Rajarajan et al. [09] investigated the impact of electrode pressure on the dimensions of the nugget, microstructure characteristics, and tensile shear strength in joints made from advanced high-strength dual-phase steel. The findings of the study highlight the crucial role of parametric optimization in attaining the desired mechanical properties [09]. The utilization of novel materials in resistance spot welding (RSW) procedures is an additional developing avenue. In their study, Das et al. [10] conducted an investigation into the application of graphene as an interlayer in resistance spot welding (RSW). They emphasized the possibility of innovative materials exerting an influence on the microstructure and mechanical properties of welds [10]. The field of resistance spot welding (RSW) is increasingly exploring the application of dissimilar material welding. In a recent study by Kekik et al. [11], the researchers investigated the impact of resistance spot welding parameters on the formation of joints between dissimilar DP1000HF and CP800 steel. The study highlighted the significance of optimizing welding parameters when joining materials with different properties [11].

Moreover, it is imperative to comprehend the intricacies associated with failure mechanisms. In their study, Siar et al. [12] utilized 3D characterisation techniques to examine the progression of interior cracks caused by liquid metal embrittlement during tensile shear testing of resistance spot welds. The aforementioned study highlights the significance of understanding the many elements of failure mechanisms [12]. The adjustment of microstructural features plays a crucial role in attaining exceptional results in resistance spot welding (RSW). The study conducted by Tian et al. [13] examined the relationship between microhardness and fatigue life in spot welding. The authors emphasized the importance of considering microstructural factors when optimizing resistance spot welding (RSW) processes [13].

Moreover, contemporary research has placed significant emphasis on the investigation of specialty materials. The study conducted by Jia et al. [14] focused on examining the microstructure and tensile shear properties of resistance spot-welded joints made from 9Cr oxide dispersion-strengthened steel. The authors emphasized the significance of comprehending and enhancing the resistance spot welding (RSW) procedures specifically for novel materials. Predictive models also have a significant function in the field of optimization. The study conducted by Májlinger et al. [15] focused on the prediction of shear tension strength in resistance spot-welded thin steel sheets. The authors emphasized the need of developing models that can evaluate the quality of welds and optimize the welding process [15]. Moreover, the role of resistance spot welding (RSW) in the automotive sector is of significant importance, and it is crucial to comprehend the methods for optimizing RSW specifically for automobile frame applications. The study conducted by Rajarajan et al. [16] examined the microstructural characteristics and tensile shear fracture behavior of resistance spot-welded advanced high-strength dual-phase steel sheets within a particular context [16]. Comprehending failure mechanisms is of utmost importance, especially in the context of dissimilar material welding. The study conducted by Prabhakaran et al. [17] focused on investigating the failure processes associated with dissimilar resistance spot welding of steels. Their research contributed to the existing body of knowledge by identifying probable failure modes and emphasizing the importance of addressing these modes for the purpose of optimization [17]. The utilization of resistance spot welding (RSW) on different materials holds significant importance across diverse industrial sectors. The study conducted by Midhun et al. [18] examined several resistance spot welding (RSW) techniques used to AISI 304 and AISI 202 materials. The research aimed to get a deeper understanding of the process of joining dissimilar materials by RSW, which holds significant importance in numerous applications [18].

In addition, it is crucial to evaluate the influence of welding flaws on the performance of joints. The study conducted by Ganjabi et al. [19] aimed to assess the impact of different strength flaws in spot welds on the strength of connections when subjected to static and cyclic loading. The findings of this research highlight the significance of defect analysis in the process of optimization [19]. Additional welding techniques are also being examined for their ability to enhance resistance spot welding (RSW). The study conducted by Kumar et al. [20] investigated the potential replacement of resistance spot welding with flexible laser spot welding in certain situations. The findings of their research suggest that the utilization of alternative approaches could potentially improve the overall effectiveness of the welding process [20]. Gaining a comprehensive understanding of fracture propagation situations is of utmost importance in the process of perfecting resistance spot welding (RSW). The experimental investigation conducted by Chanh et al. [21] focused on elucidating the three-dimensional crack propagation phenomenon in resistance spot welds. The study underscored the importance of understanding failure mechanisms and crack propagation in order to optimize the welding process [21]. Moreover, the optimization of resistance spot welding (RSW) extends beyond the limitations of ordinary steel materials. The study conducted by Elitas and Erden [22] was to examine the impact of various welding parameters on the tensile properties and failure modes of non-alloyed steel manufactured using powder metallurgy. The researchers emphasized the significance of comprehending material-specific parameters in order to optimize the welding process. The utilization of real-time monitoring has also been recognized as a valuable technique for enhancing the efficiency of resistance spot welding (RSW) procedures. In their study, Butsykin et al. [23] conducted an assessment of the dependability of resistance spot welding control by employing on-line monitoring of dynamic resistance. Their findings underscored the significance of real-time monitoring in the optimization of resistance spot welding processes.

Furthermore, the examination of the effects of elevated temperature heat input on the morphological and mechanical properties of duplex stainless steel underscores the importance of regulating heat input to achieve the desired welding attributes [24], [25], [26], [27]. The aforementioned investigations collectively highlight the imperative requirement for additional examinations and enhancements in resistance spot welding procedures. These investigations encompass a range of aspects, including material combinations, parameter adjustments, and innovative welding techniques, all aimed at attaining enhanced joint integrity, mechanical properties, and performance tailored to specific applications.

Resistance Spot Welding (RSW) is a crucial method of joining that is extensively employed across several sectors because to its high efficiency and strong structural integrity [28], [34]. Despite its importance, there is an urgent requirement for additional research and improvements in the field of RSW due to many factors emphasized in recent studies. The ongoing research on RSW, exemplified by the works of Deshmukh and Kharche [34], has emphasized the importance of processing conditions on the mechanical characteristics, namely the tensile strength and failure patterns, of welded joints in materials such as SS 316L. These investigations have emphasized the importance of comprehending the impact of different factors on the effectiveness and dependability of resistance spot welding (RSW) connections.

The optimization of resistance spot welding (RSW) parameters continues to be a central focus in current research [29], [30], [31], [33]. An investigation into the impact of parameters on the welding process, including heat input, current, and pressure, is essential for improving the overall efficiency and quality of spot-welded joints. Research conducted by Kakade et al. [31] and [33] has explored the relationship between welding parameters and the occurrence of defects, highlighting the importance of accurately optimizing these parameters to address such problems. Furthermore, the studies conducted by Deshmukh and Kalyankar [32], [35], [36], [38] and Naik et al. [37] have provided valuable insights into the importance of heat treatment in influencing the microstructure and characteristics of materials after resistance spot welding (RSW). These findings suggest that heat treatment could be a promising approach for improving the mechanical properties of welded joints.

Furthermore, studies conducted by Chaudhari and Deshmukh [39] and Bhoskar et al. [40] have emphasized the importance of comprehending the corrosion behavior and metallurgical properties of welded materials in order to enhance our understanding of their performance and durability after resistance spot welding (RSW). These investigations have opened up opportunities for further research in this area. To summarize, recent studies emphasize the need for thorough examinations of the RSW process. This includes optimizing welding parameters, studying the impact of heat treatment, and conducting metallurgical analyses. These investigations aim to improve the mechanical properties and longevity of spot-welded joints in different materials.

2. Methods and materials

Within the field of materials science and welding technology, the utilization of Response Surface Methodology (RSM) via the Box-Behnken design approach has demonstrated its efficacy as a robust and methodical tool for examining welding parameters. This is particularly relevant in the context of enhancing the resistance spot welding (RSW) process for joints made from 316L stainless steel. Response surface methodology (RSM) is a statistical approach utilized to construct a mathematical correlation between several independent variables, specifically welding parameters, and a collection of response variables, which encompass joint attributes and performance [03]. The utilization of a Box-Behnken design facilitates the development of a well-balanced and highly efficient experimental plan, hence enabling researchers to efficiently investigate the parameter space and derive significant results. The Box-Behnken Design is a statistical experimental design technique that is widely used in several fields of research and experimentation. The Box-Behnken design is a response surface design that is known for its capacity to estimate the major effects and interactions of factors, eliminating the necessity for a whole factorial experiment [01]. In the present study, the parameters are manipulated at three distinct levels: low (-1), center (0), and high (+1), thereby facilitating a thorough investigation of the parameter space while minimizing the number of experimental trials required in comparison to a complete factorial design.

Benefits of the Box-Behnken Design:

- **Balanced Exploration:** The Box-Behnken design offers a well-balanced examination of the parameter space, making it especially beneficial in situations when the number of tests must be limited, a common occurrence in resource-intensive studies.
- **Efficient Factorial Design:** The design incorporates three levels for each factor, enabling the examination of linear, quadratic, and interaction effects. This comprehensive approach enhances the design's efficacy in elucidating the complex interplay between welding settings and joint features.
- **Optimization Capability:** The utilization of Response Surface Methodology (RSM) in conjunction with the Box-Behnken design enables researchers to not only assess the impacts of welding parameters but also improve them in order to attain the desired attributes of the joint [02].

Application to 316L Stainless Steel Welding:

The utilization of Response Surface Methodology (RSM) in conjunction with the Box-Behnken design for the analysis of welding parameters in 316L stainless steel joints offers numerous significant benefits. The aforementioned substance is extensively employed in several industries that prioritize attributes such as resistance to corrosion, mechanical robustness, and the integrity of joints. These industries include but are not limited to the medical, aerospace, and nuclear sectors. Through a methodical manipulation of welding current, electrode force, and other relevant parameters, and subsequent analysis of their impact on joint characteristics, such as tensile strength and failure patterns, researchers are able to construct mathematical models that elucidate the correlations between these parameters and the weld quality. These models enable the optimization of the welding process in order to attain the desired joint properties and performance, while simultaneously reducing the need for conducting numerous experiments.

The primary objective of this research is to conduct a comprehensive examination of the impact of welding current and electrode force on both the tensile strength and failure pattern of Resistance Spot Welding (RSW) joints in 316L stainless steel. This particular material is renowned for its exceptional corrosion resistance and mechanical properties, making it an ideal candidate for this investigation [04]. In order to methodically examine the impacts of these variables, a Design of Experiments (DOE) methodology is utilized, specifically employing Response Surface Methodology (RSM) and making use of the Box-Behnken design.

Material Specifications:

The primary material employed in this study is 316L stainless steel, renowned for its distinctive chemical composition that adheres to the specified criteria (ASTM A240/A240M). The composition of the substance is outlined in Kumar et al.'s [20] study.

- Carbon (C%): 0.022%
- Manganese (Mn%): 1.25%
- Phosphorus (P%): 0.045%
- Sulfur (S%): 0.004%
- Silicon (Si%): 0.42%
- Chromium (Cr%): 16.16%
- Nickel (Ni%): 10.03%
- Molybdenum (Mo%): 2.06

Specimen's Preparation

SS 316L metal sheet having thickness of 0.4 mm is cut on EDM machine into 30 pieces' dimension of 100 mm x 25 mm. The base metal was singly cut into plates of dimensions (100 x 25) mm (L x W) and lap-jointed with dimensions (15 x 15) mm according to the AWS C1.1M/C1.1:2012 standard as shown in figure 1.

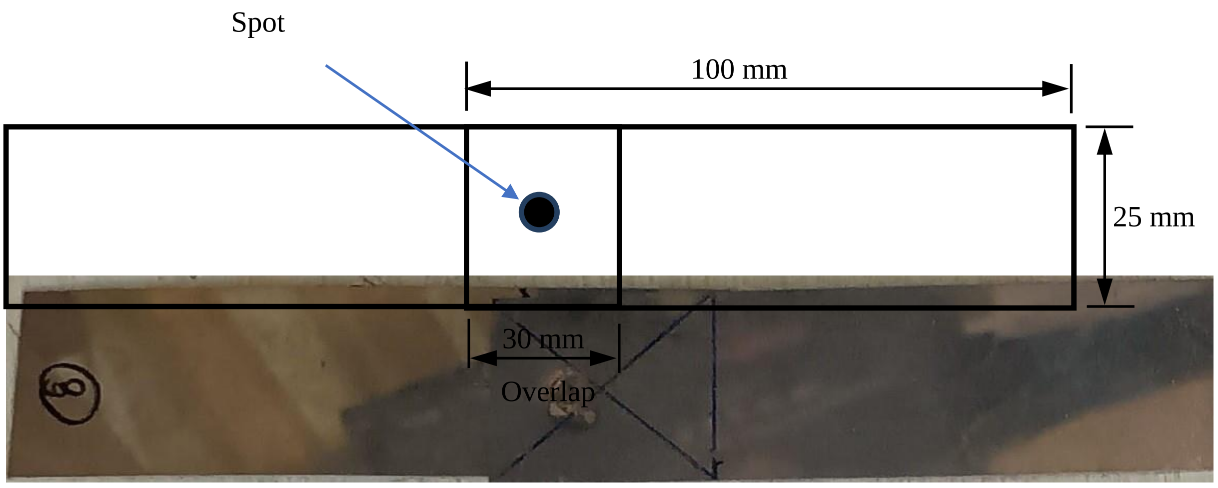


Fig. 1 Sample Specimen

3. Experimental Setup:

The experimental design is formulated using a Box-Behnken design, which offers a well-balanced and efficient exploration of the parameter space. The experimental design incorporates three levels (-1, 0, +1) for each parameter, leading to a factorial experiment with 3^2 conditions.

The parameters of the welding process and their corresponding levels are as follows and shown in figure 2 and 3:

- Welding Current (KA): 6, 8, and 10 KA [05].
- Electrode Force: 2, 4, and 6 bar.
- Weld Time: 4, 6, and 8 cycles [09].
- Squeeze Time: 35 seconds (constant).

Fig. 2 Experimental setup

Fig. 3 Digital display of control panel

4. Design of Experiment (DoE) And Results:

The Table 1 shows the Design of experiements combinations and the DoE result – Tensile Strength.

Table 1: Design of Experiment with testing results

Sr. No.	Welding current (KA)	Pressure (Bar)	Weld time (Cycle)	Tensile Stength (Kgf)
1	8	2	4	259.11
2	10	4	4	271.50
3	6	2	6	219.12
4	8	6	4	249.18
5	8	4	6	250.00
6	6	4	4	250.00
7	10	6	6	285.05
8	8	4	6	250.00
9	8	2	8	247.58
10	6	6	6	135.00
11	10	4	8	315.02
12	6	4	8	193.60
13	8	6	8	247.10
14	10	2	6	212.80
15	8	4	6	251.00

Figure 4 are the speciments prepared after Spot Weld of above combination and marked with numbers. These specimens are prepared in the in one of the welding Industry at Nashilk.

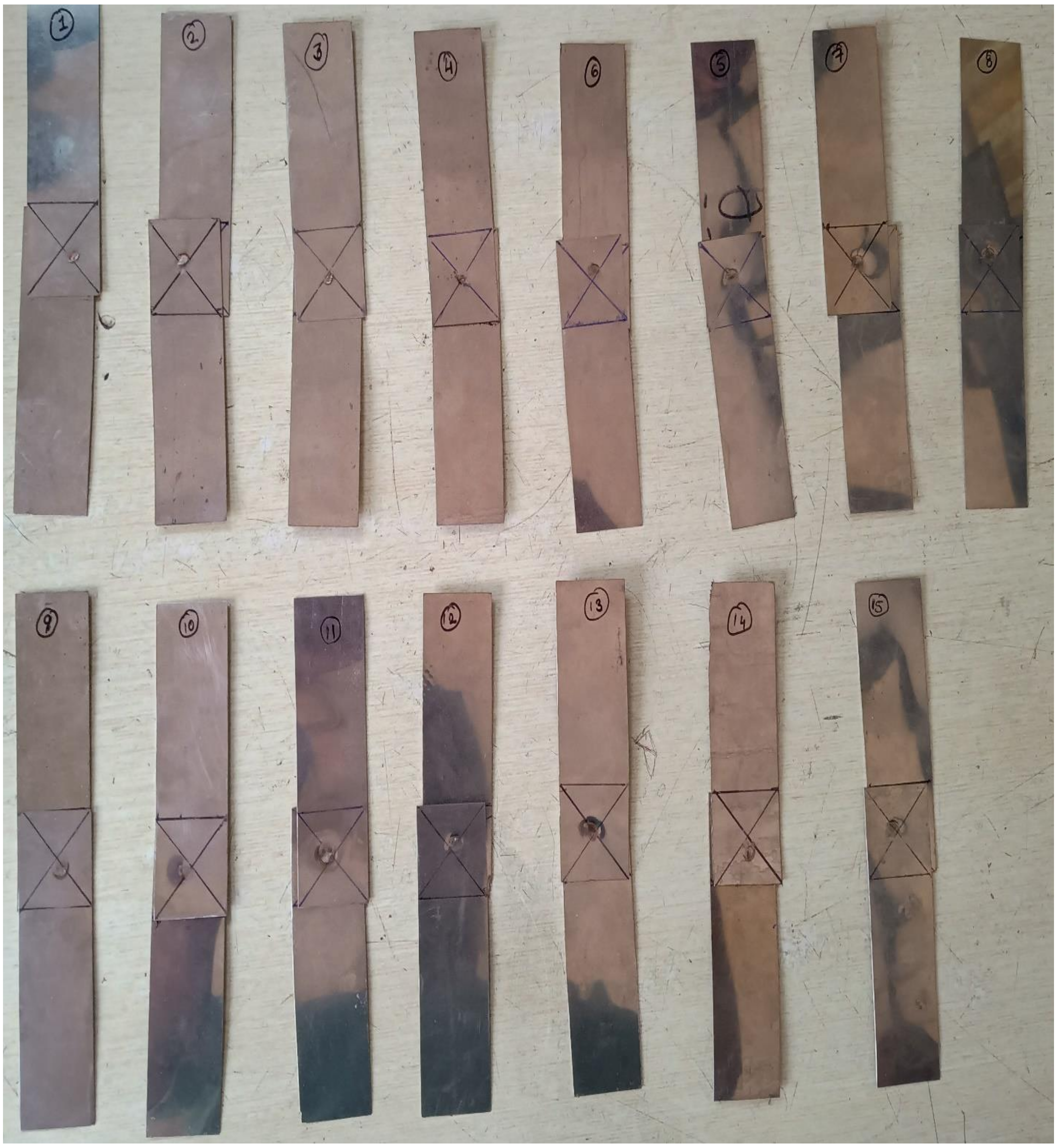


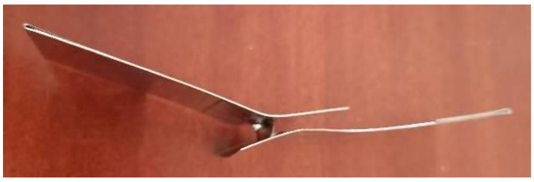
Fig. 4 DoE samples

5. Experimental Test

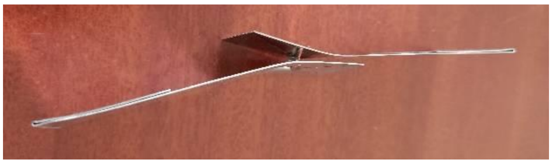
The tensile-shear tests were conducted on spot welding specimens using a WDW-300Y Series Universal Testing Machine with a load capability of 20 KN in the well equipment company in the Nashik. The tests were performed at a crosshead speed of 10 mm/min. The specimens were securely held using shims that had the same thickness as the welding specimens. To determine the tensile stress values for the two samples with the greatest and lowest results in the tensile-shear tests, conducted on an exposed area of 1 cm^2 using the potentiated and cyclic anodic polarization technique as per the ASTM G 5-9430 standard. Figure 5 shows the UTM test results of the specimens.

1. Tensile Strength = 259.11 kgf

2. Tensile Strength = 271.50 kgf

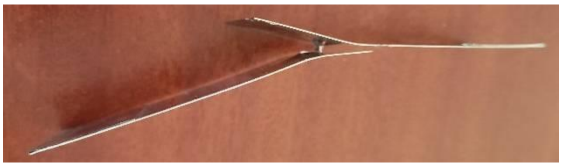


3. Tensile Strength = 219.12 kgf

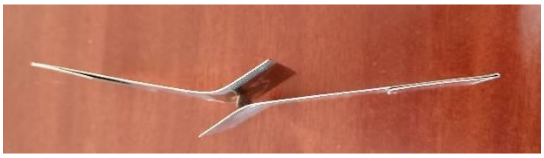


4. Tensile Strength = 249.18 kgf

5. Tensile Strength = 250.00 kgf

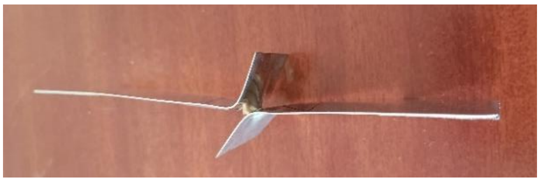


6. Tensile Strength = 250.00 kgf



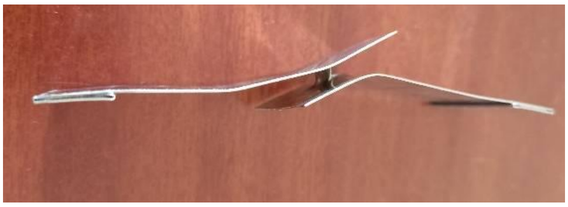
7. Tensile Strength = 285.05 kgf

8. Tensile Strength = 250.00 kgf



9. Tensile Strength = 247.58 kgf

10. Tensile Strength = 135.00 Kgf

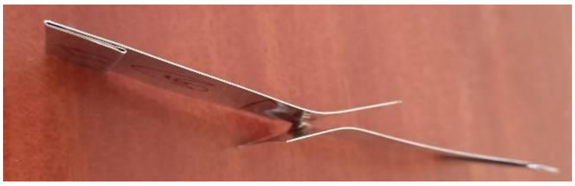


11. Tensile Strength = 315.02 kgf

12. Tensile Strength = 193.60 kgf

13. Tensile Strength = 247.10 kgf

14. Tensile Strength = 212.80 kgf



Tensile Strength = 251.00 kgf

Fig. 5 Specimens after UTM Test

Response Surface Regression: Tensile strength (Kgf) weld time (Cycle)

Table 2 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	23894.1	2654.9	12271.41	0.000
Linear	3	10420.8	3473.6	16055.58	0.000
Welding current (KA)	1	10271.0	10271.0	47474.49	0.000
Pressure (Bar)	1	62.0	62.0	286.81	0.000
Weld time (Cycle)	1	87.7	87.7	405.43	0.000
Square	3	4842.1	1614.0	7460.31	0.000
Welding current (KA)*Welding current (KA)	1	861.7	861.7	3982.92	0.000
Pressure (Bar)*Pressure (Bar)	1	1797.5	1797.5	8308.44	0.000
Weld time (Cycle)*Weld time (Cycle)	1	1864.8	1864.8	8619.45	0.000
2-Way Interaction	3	8631.2	2877.1	13298.34	0.000
Welding current (KA)*Pressure (Bar)	1	6112.9	6112.9	28254.87	0.000
Welding current (KA)*Weld time (Cycle)	1	2496.0	2496.0	11536.96	0.000
Pressure (Bar)*Weld time (Cycle)	1	22.3	22.3	103.19	0.000
Error	5	1.1	0.2		
Lack-of-Fit	3	0.4	0.1	0.42	0.762
Pure Error	2	0.7	0.3		
Total	14	23895.2			

Model Summary:

S	R-sq	R-sq(adj)	R-sq(pred)
0.465133	100.00%	99.99%	99.97%

Table 3 Coded Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	250.333	0.269	932.19	0.000	
Welding current (KA)	35.831	0.164	217.89	0.000	1.00
Pressure (Bar)	-2.785	0.164	-16.94	0.000	1.00
Weld time (Cycle)	-3.311	0.164	-20.14	0.000	1.00
Welding current (KA)*Welding current (KA)	-15.277	0.242	-63.11	0.000	1.01
Pressure (Bar)*Pressure (Bar)	-22.064	0.242	-91.15	0.000	1.01
Weld time (Cycle)*Weld time (Cycle)	22.473	0.242	92.84	0.000	1.01
Welding current (KA)*Pressure (Bar)	39.092	0.233	168.09	0.000	1.00
Welding current (KA)*Weld time (Cycle)	24.980	0.233	107.41	0.000	1.00
Pressure (Bar)*Weld time (Cycle)	2.362	0.233	10.16	0.000	1.00

Table 4 Regression Equation in Un-Coded Units

Tensile stength (Kgf) = 618.76 + 2.46 Welding current (KA) - 38.993 Pressure (Bar)
- 121.398 Weld time (Cycle)
- 3.8192 Welding current (KA)*Welding current (KA)
- 5.5160 Pressure (Bar)*Pressure (Bar)
+ 5.6183 Weld time (Cycle)*Weld time (Cycle)
+ 9.7731 Welding current (KA)*Pressure (Bar)
+ 6.2450 Welding current (KA)*Weld time (Cycle)
+ 0.5906 Pressure (Bar)*Weld time (Cycle)

Effects Pareto for Tensile stength (Kgf)

The effects Pareto for Tensile Strenght is shown in the following graph (Figure 6).

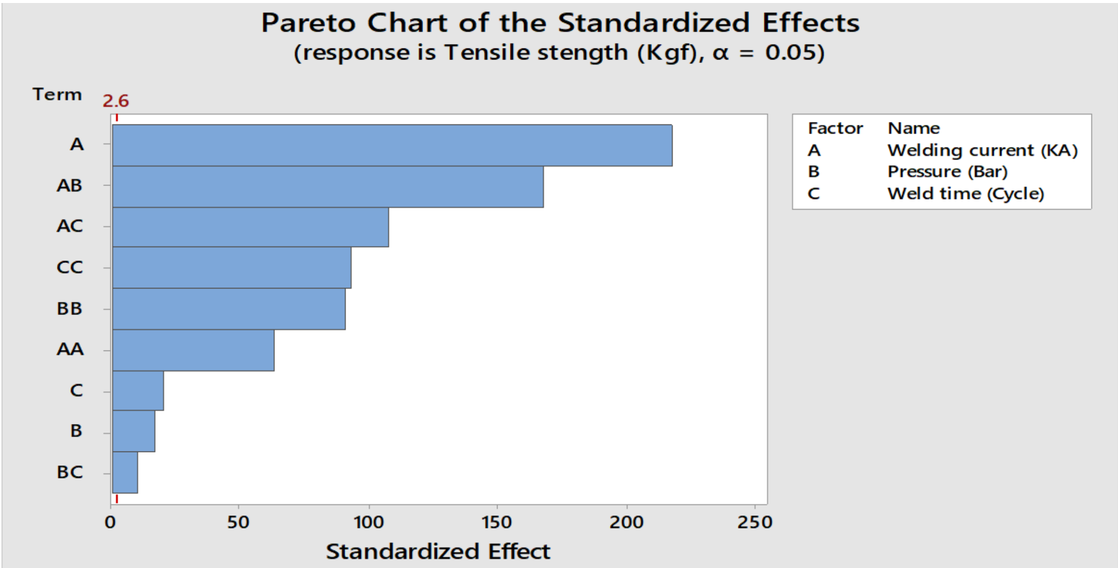


Fig. 6 Effects Pareto for Tensile strength (Kgf)

Main effects plot for tensile strength vs current, pressure and weld time is shown in figure 7.

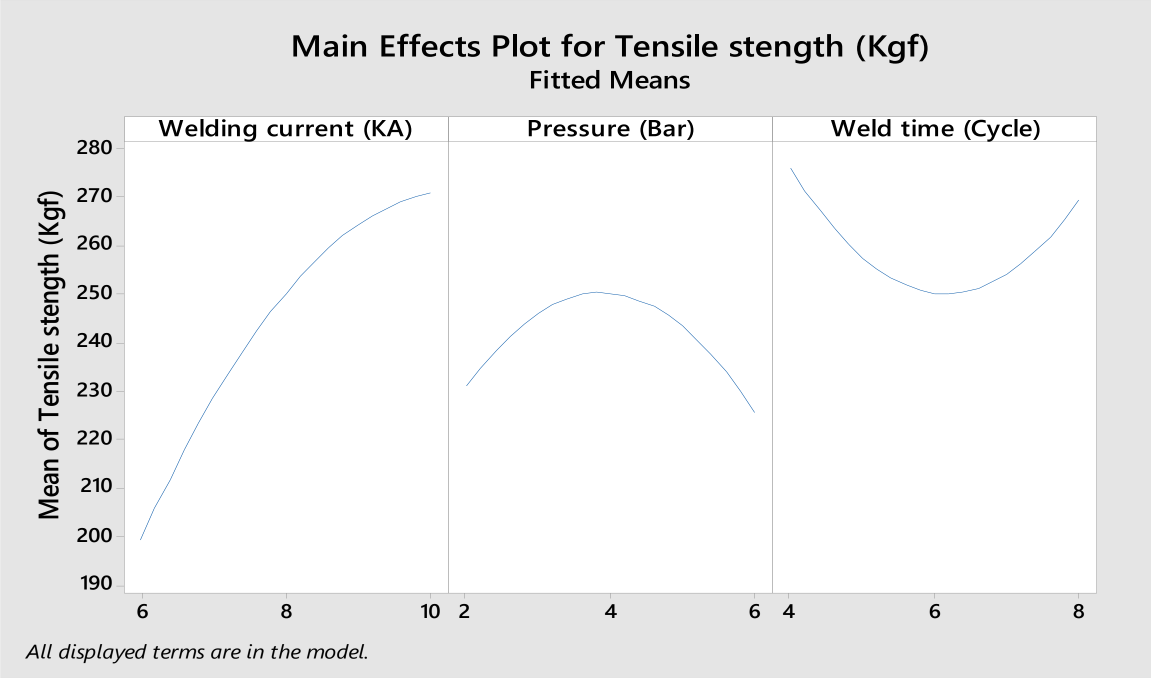


Fig. 7 Main Effects Plot for Tensile Strength (Kgf)

The mean fitted interaction plot for tensile strength vs pressure, welding current is displayed in figure 8.

Fig. 8 Interaction Plot for Tensile Strength (Kgf)

Figure 9 shows the surface plot of tensile strength vs welding time, pressure.

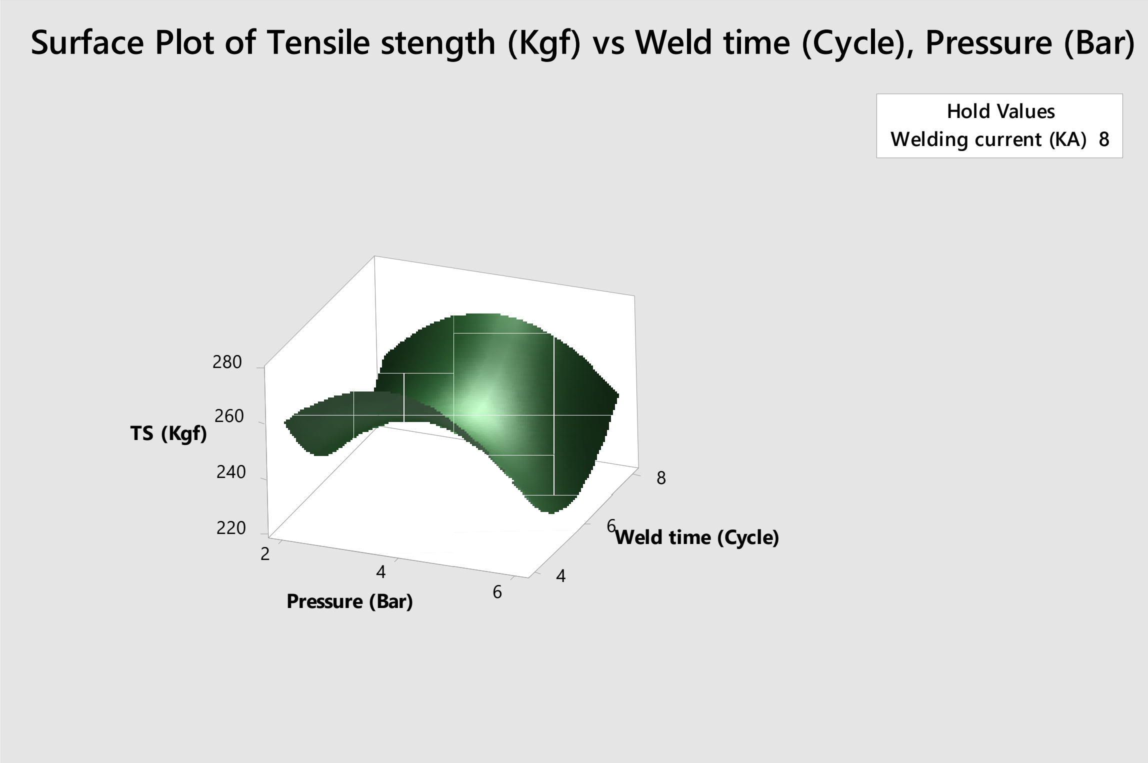


Fig. 9 Surface Plot of Tensile Strength (Kgf) VS Weld Time (Cycle), Pressure (Bar)

Figure 10 shows the surface plot of tensile strength vs welding current, pressure.

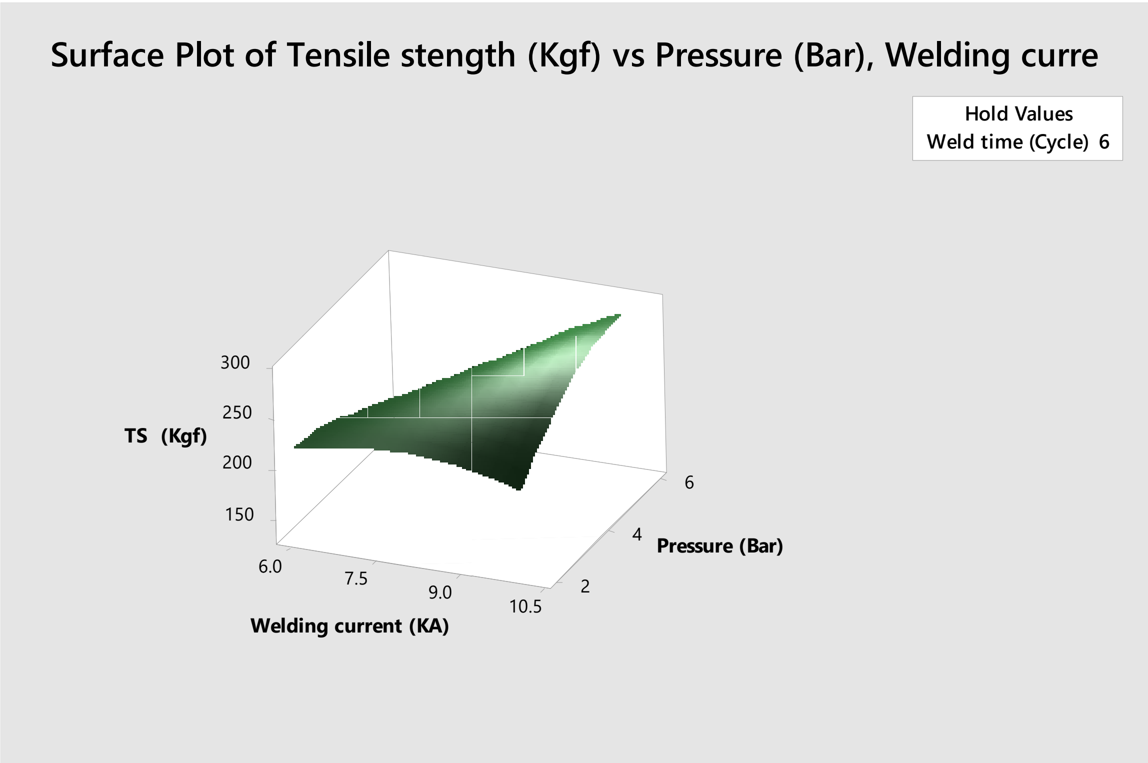


Fig. 10 Surface Plot of Tensile Strength (Kgf) VS Pressure (Bar), Welding Current (KA)

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6. Response Optimization: Tensile stength (Kgf)

Table 4 Parameters and Solution

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Tensile stength (Kgf)	Maximum	135	315.02		1	1

Solution

Solution	Welding current (KA)	Pressure (Bar)	Weld time (Cycle)	Tensile stength (Kgf) Fit	Composite Desirability
1	10	5.75758	8	331.973	1

Multiple Response Prediction

Variable	Setting
Welding current (KA)	10
Pressure (Bar)	5.75758
Weld time (Cycle)	8

Response	Fit	SE Fit	95% CI	95% PI
Tensile stength (Kgf)	331.973	0.510	(330.663, 333.284)	(330.199, 333.747)

Optimization Plot

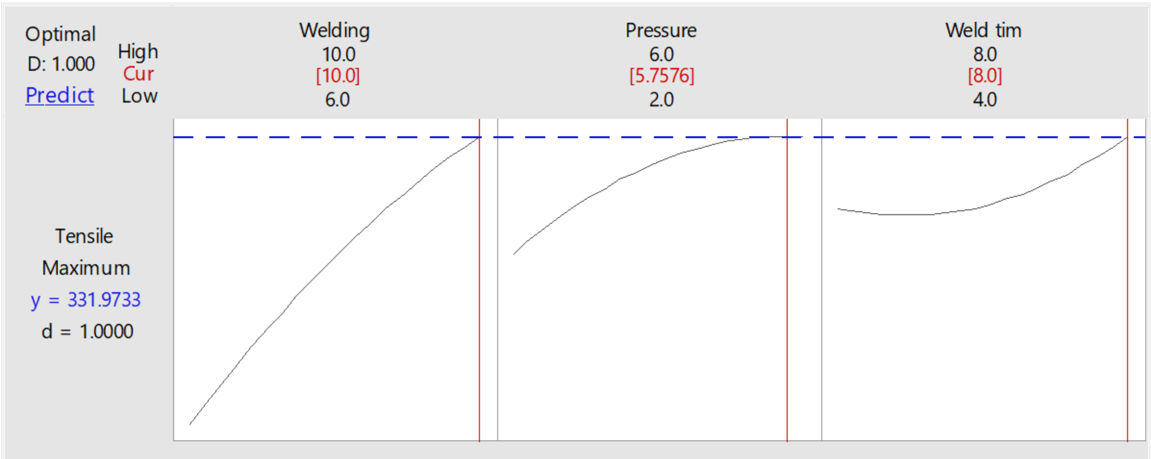

Fig. 11 Optimized solution for RSW 316L

7. Conclusion

In conclusion, the influence of resistance spot welding (RSW) process parameters on joint characteristics and performance is a critical factor to consider in ensuring the quality and reliability of welded joints. Through extensive research and experimentation, it has been established that the selection and optimization of RSW process parameters have a significant impact on various aspects of joint quality, such as weld nugget size, mechanical properties, and overall performance. The process parameters, including welding current, welding time, electrode force, and electrode material, directly affect the heat input, thermal cycles, and pressure applied during the welding process. By carefully adjusting these parameters, it is possible to control the formation of the weld nugget, which plays a vital role in determining joint strength and integrity. Moreover, the proper selection of process parameters can help mitigate issues such as weld defects, including porosity, cracking, and insufficient penetration.

- The optimization of RSW process parameters also leads to improved joint performance. By achieving the desired weld quality and integrity, the joints exhibit enhanced mechanical properties, including tensile strength, fatigue resistance, and corrosion resistance. These characteristics are crucial for ensuring the structural integrity and longevity of welded components in various industries, such as automotive, aerospace, and construction.

- Furthermore, the influence of RSW process parameters extends beyond joint characteristics. It also affects process efficiency and cost-effectiveness. By optimizing the parameters, manufacturers can reduce energy consumption, production time, and material waste, leading to improved productivity and economic viability.

In summary, understanding and controlling the influence of RSW process parameters on joint characteristics and performance is essential for achieving high-quality and reliable welded joints. Proper parameter selection and optimization result in improved joint strength, mechanical properties, and overall performance. Moreover, it enhances process efficiency and cost-effectiveness. Continued research and development in this field will contribute to further advancements in resistance spot welding technology, ultimately benefiting various industries that rely on welded components.

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