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An Experimental Investigation of the Effect of Spot-Welding Process Parameters on the Braking Load of Similar Metal Joints

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Abstract:- Applied in automotive, aerospace, and structural applications needing high welding quality and mechanical performance, resistance spot welding (RSW) is a critical connecting method. The effects of welding pressure on the tensile strength of the most important RSW process parameters—that of welding stream, compressed time, welding time, retention time, and low tolerance (HSLA) high strength 355 steel connections—are investigated in this work. 22 experimental studies in all were carried out using Response surface method and a pneumatically controlled resistance welding machine with a box 10 configuration. Joint resistance is shown to be most influenced by weld current, retention time, and welding time in experimental findings. Maximum tensile strength of 1.152 kN/mm² came from optimized welding settings for 6 ka welding current, hold times of 14 ms, 25 ms, and 4 kN welding pressure. Advanced prediction models including artificial neural networks (ANNs) and finite element analysis (FEAs) will be used in next work to enhance parameter selection and process efficiency.

Keywords: *HSLA, RSW, FEA.*

Introduction

Popular and often used technique of welding metallic materials in many different fields is resistance spot welding (RSW). Its efficiency and power in generating long-lasting bonds are well known. Still, there is a huge requirement to do extensive inspections of the Resistance Spot Welding (RSW) method since many industries are changing and demand welded parts to show better degrees of performance and durability. Recent studies have not only underlined the importance of this criterion but also aimed to keep its efficacy and efficiency as a joining method by looking at its parametric impacts, hence improving RSW. Many recent studies show how much more study in the subject of RSW is needed. With an aim of improving process parameters, Ding et al. [04] underlined the need of optimizing resistance spot welding (RSW) techniques for high strength materials.

The aim of the work is to evaluate the effect on tensile strength of connections between identical metals with various spot-welding settings. Important components of research include welding time, electrode force, and welding current. By meticulously adjusting these elements, the study aims to identify ideal circumstances for maximum tensile strength in spot-welded joints.

Resistance spot welding (RSW) is obviously a crucial joining technique in the automotive industry, given around 6000 spot welds used in a conventional vehicle body (Lee et al., 2017). The lifetime and performance of automotive components depend significantly on the quality of these welds. Several research have examined how welding parameters affect joint quality, so confirming that primary determinants of weld strength and nugget growth are factors including welding current, welding time, and electrode pressure (Bagal et al., 2021; Rajarajan et al., 2022). Fascinatingly, various studies have shown that other elements can also be fairly significant even although time and welding current are always found to be crucial. For some thicknesses of austenitic stainless steel, for example, pulse welding and holding time were demonstrated to be the most important elements (Mezher, Carou, et al., 2024). Moreover affecting the optimal welding conditions is the material being welded; high strength steel sheets require less welding currents than mild steel sheets (Oikawa et al., 2007). RSW parameter adjustment is thus extremely essential to generate high-quality welds in automotive applications. Advanced technologies such finite element modeling (Lee et al., 2017) and artificial neural networks (Mezher et al., 2024) are projected to optimize process parameters and weld quality. These techniques as well as experimental study will help to improve the dependability and performance of spot-welded joints in the automobile industry.

Industries like automotive make extensive use of resistance spot welding (RSW) to join sheet metal including AISI 304 stainless steel. For this material, several studies have looked at how RSW settings affect weld quality. Welding current, welding time, electrode pressure, and holding time—key factors investigated—Mezher et al., 2024; Vigneshkumar et al., 2018 Important weld parameters such nugget diameter, tensile shear strength, microhardness, and microstructure (Kumar et al., 2020) are strongly influenced by these elements. Fascinatingly, depending on sheet thickness, some studies found pulse welding or holding time to be most relevant while others found welding current to be the most crucial factor influencing tensile strength and nugget diameter (Kumar et al., 2020). This emphasizes how complicatedly factors interact. Furthermore discovered to be higher in the nugget zone than in the heat-affected zone and base metal (Mezher, Carou, et al., 2024) was microhardness. Artificial neural network (ANN) modeling has been effectively used to maximize RSW parameters and anticipate results. Good capacity of ANN models to capture the nonlinear interactions in RSW processes (Zaharuddin et al., 2017) has been demonstrated. Multiple investigations indicated that the Levenberg-Marquardt training function with log sigmoid transfer function produced the best prediction results (Mezher et al., 2024; Mezher et al., 2024). Comprehensive optimization of RSW parameters is made possible by this combination of experimental analysis and ANN modeling, therefore enabling desired weld quality in AISI 304 stainless steel joints. In resistance spot welding, two faying surfaces are heatedly joined to form a lap joint. Known as a nugget, a single spot-like weld results. Heat generates from the resistive passage of current, which moves across sheets and induces fusion. The metal fused and a nugget was produced when the temperature was elevated to the plastic limit of the metal. The current is also shut off, allowing the weld nugget to cool gradually until it freezes below pressure (Singh Bharaj et al., 2023).

This work optimizes resistance spot welding (RSW) settings for TRIP steel using response surface methodology (RSM). The researchers apply a second-order model to forecast the optimal welding circumstances considering the need of lightweight, high-strength materials in the automotive sector. Key factors like welding current, time, and force were looked at to maximize shear strength while minimizing indentation. While offering a methodical approach to raise weld quality in TRIP and galvanized TRIP steel applications, the work greatly reduces experimental efforts (Kim et al., 2005). Fascinatingly, although this work focuses on TRIP steel, other materials and welding procedures have been used using similar optimization strategies. For instance, while Plaine et al., 2015 use RSM for friction spot welding of aluminum and titanium alloys, Rajarajan et al., 2022 explain the use of RSM for optimizing RSM parameters in advanced high strength steel (AHSS) joints. At last, for a range of materials and welding techniques, optimizing resistance spot welding settings by means of response surface techniques is a practical approach. It improves weld quality in automotive uses by means of effective parameter tweaking, therefore minimizing the need for expensive trial-and-error efforts.

Response surface methodology (RSM) and Box-Behnken design (BBD) have been employed in several research to find the ideal welding settings for different materials. Emphasizing the need of welding current, welding time, and electrode force in generating excellent mechanical qualities, Dahake et al. (2023) examined the optimization of RSW parameters for 316L stainless steel. Their results revealed that raising these elements enhances general weld quality (Dahake et al., 2023) as well as joint features.

(Choudhari et al., 2025) demonstrates significant progress in Resistance Spot Welding (RSW) technologies, focusing on parameter optimization, dissimilar material joining, and microstructural behavior. Recent studies highlight the integration of AI-based monitoring systems and hybrid welding methods to enhance weld quality. Notably, dissimilar metal welding and fatigue analysis have emerged as critical research domains. Microstructure-property correlations are extensively studied to improve joint performance. This comprehensive review underscores the evolving landscape of RSW and its industrial applicability

(Choudhari et al., 2025) highlights extensive research on resistance spot welding (RSW), emphasizing its application in joining high-strength materials across industries. Prior studies focus on optimizing process parameters such as welding current, electrode force, and time to improve joint strength and reduce defects. Researchers underline the significance of microstructural analysis in understanding weld performance and failure mechanisms. Studies also explore the effects of electrode geometry, cooling rates, and material combinations on weld quality. Collectively, the literature suggests a critical need for continued investigation into parameter optimization for enhancing RSW reliability and efficiency.

Materials & Method

The efficiency of Responsive Surface Methodology (RSM) of Box-Dehnken type in optimization and control of welding processes is demonstrated by the conducted research on welding technologies. This is crucial during the resistance welding RSW procedure that is raising single steel joints in HSLA 355 grade's strength. RSM develops mathematical relationships between several independent welding factors and the response features including common properties and the resulting outcome. Design of Box 10 is efficient in evaluating the factors since it shows a sufficient representation of a complete factorial design and consequently eliminates the total number of factorial tests carried out. Three levels (-1), medium (0), and high (+1) were also sought to be used in order to assure high quality optimization results and permit factor reduction.

Material Specifications:

HSLA (High-Strength Low-Alloy) steel 355 is a type of structural steel with good mechanical properties and high strength. HSLA (High-Strength Low-Alloy) steel 355 typically has the following chemical composition:

- Carbon (C): 0.20% max
- Manganese (Mn): 1.60% max
- Silicon (Si): 0.50% max
- Phosphorus (P): 0.035% max
- Sulfur (S): 0.035% max
- Vanadium (V): 0.05-0.15%
- Niobium (Nb): 0.02-0.05%
- Titanium (Ti): 0.02-0.05%

Specimen Preparation

HSLA 355 metal sheet with a thickness of 3 mm is cut into 22 pieces of 100 mm x 25 mm using an EDM machine. The base metal was cut into plates measuring (100 x 25) mm (L x W) and lap-jointed with dimensions of (25 x 25) mm in accordance with the AWS C1.1M/C1.1:2012 standard, as illustrated in figure 1.

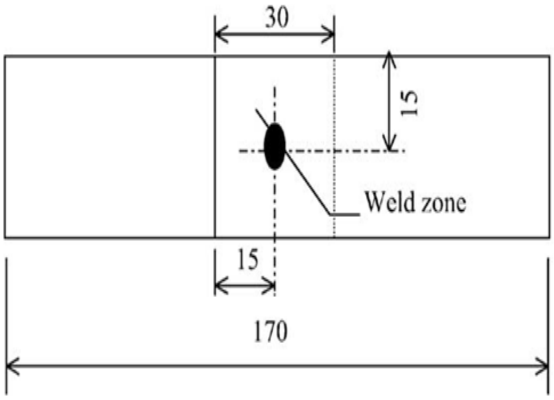


Fig. 1 Sample Specimen

The finalized maximum and minimum parameter ranges are outlined below, representing the optimal limits determined through the experimentation process.

Table .1 Process parameter and ranges

Parameter	**Min**	**Max**
Welding Current	6	10
Squzzee Time	30	50
Hold Time	8	20

Weld Time	15	30
Welding Pressure	3.5	4.5

Resistance Spot Welding Machine Specifications

Here the Kirti Pressing Pvt performs. I utilized the RSW welding equipment from Janak Industries. The nominal output of the machine is rather large at 125 kVa, and the maximum welding current is at 24 ka. Its AK-54 V control unit allows fine tweaking of the parameters. The welding time has the lowest setting of 10 MS. Good mechanical performance of a cooling system depends on water pressure of 2 kg/cm² and flow of 6 L/min. The machine has a 300 mm arm gap and a 150 to 984 kg-F electrode force range. The specifications altogether are 1050mm length by 410mm breadth and height of 1780mm moreover weighing from 680 kg. Since they must be welded to HSLA355 grade stainless steel welds to be of resistance, accuracy, and consistency, this kind of machine is able to weld highly accurate and consistently HSLA 355 stainless steel samples.

Fig.2 Experimental setup

Experimental Test

The experiment was conducted to investigate the resistance spot welding (RSW) of HSLA 355 stainless steel specimens, each measuring **25 mm × 100 mm**. Welding trials were performed using a **pneumatic-controlled resistance spot welding machine** with varying process parameters: **welding current, squeeze time, weld time, hold time, and welding pressure**. The welded samples were evaluated for **tensile strength, nugget formation, and microstructural characteristics**. A **Box-Behnken design** was applied for optimization, and mechanical testing was performed to assess joint quality and performance.

Table 2. Observation after welding

Expt. No.	Welding Current	Squeeze Time	Hold Time	Weld Time	Welding Pressure	Observation
1	6	40	14	20	3.5	not properly weld as per criteria
2	10	35	12	15	4.5	not properly weld as per criteria
3	8	45	8	30	4	not properly weld as per criteria
4	9	40	16	25	3.5	not properly weld as per criteria
5	7	35	10	20	4.5	Both side welding formation
6	6	30	14	25	4	Both side welding formation
7	10	40	16	20	3.5	not properly weld as per criteria
8	8	50	20	30	4.5	Both side welding formation
9	9	45	8	15	3.5	Both side welding formation
10	7	40	10	20	4	not properly weld as per criteria
11	8	35	12	25	4.5	Both side welding formation
12	7	40	14	30	3.5	Both side welding formation
13	10	35	16	20	4	not properly weld as per criteria
14	6	45	18	15	3.5	Both side welding formation
15	7	40	20	30	4.5	Both side welding formation
16	9	35	8	15	4	Both side welding formation
17	8	45	10	20	3.5	not properly weld as per criteria
18	7	40	12	25	4.5	Both side welding formation
19	9	35	14	30	4	Both side welding formation
20	8	40	16	20	3.5	not properly weld as per criteria
21	10	45	18	15	4	not properly weld as per criteria
22	6	35	20	20	4.5	Both side welding formation

Using the above parameters, 22 experiments conducted in Janak Industry ,Ambad MIDC Nashik. The following specimen represents the finalized experiment, completed with proper welding

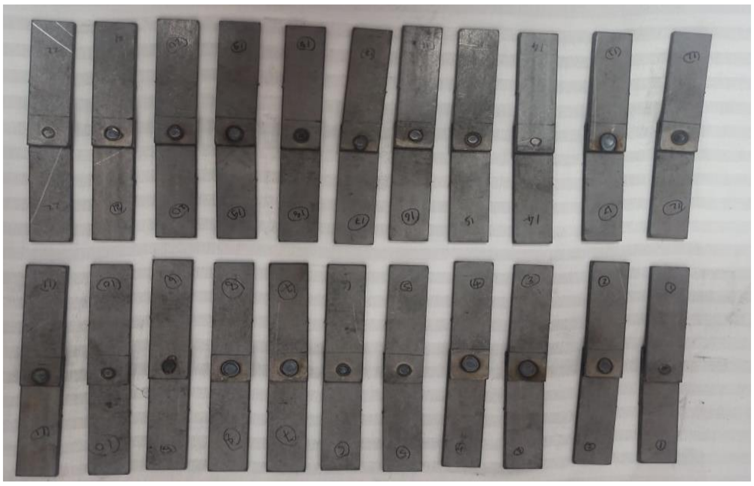


Fig. 3 shows the 22 sample after resistance spot weld joint

Evaluation and selection of samples properly welded with resistance spot weldingResistance spot welding (RS W) is a wide range of connection processes in the manufacturing industry due to its efficiency and applicability i n a variety of metal arrangements. However, guaranteeing high quality welded seams is important to maintain th e structural integrity and mechanical strength of the weld components. In this study, inspections were performed according to the disc to assess the quality of the welded joints, and defective samples were removed so that only welding connections were appropriately considered for further analysis. Welded joint defects with problems suc h as inadequate mergers, porosity, excessive splashes, or inappropriate nugget formation were excluded from su bsequent testing stages. The main reasons for these defects are inappropriate welding streams, incompatible elec trode mismatch, insufficient pressure, or inconsistency in material. To maintain the integrity of the study, only w elded seams that met strict quality standards were selected for further mechanical and metallurgical characterizat ion.

After the inspection process, samples were identified as appropriate welding quality at 5, 6, 8, 9, 10, 14, 15, 16, 18, 18, 22, 22. Selected samples undergo additional evaluations such as train tests, microstructure analysis, and cure tests to continue verifying performance under operating conditions. This approach ensures that weld seams meet industrial standards and improve general durability for welding meetings. Future work will focus on optimi zing welding parameters to minimize the formation of errors and improve the efficiency of the resistance spot pr ocess.

	
Sample No 5	Sample No 6
	
Sample No 8	Sample No 9
	
Sample No 10	Sample No 12
	
Sample No 14	Sample No 15
	
Sample No 16	Sample No 18
	
Sample No 19	Sample No 22

Table 3. Tensile test report

Sam ple . No.	Welding curent	Squeeze time	Hold time	Weld time	Welding pressure	Max force Kn	Dipsplaceme nt mm	Ax disp mm	Tensile stregnth Kn/mm2
1	6	40	14	20	3.5	Above sample is not properly weld as per criteria			
2	10	35	12	15	4.5	Above sample is not properly weld as per criteria			
3	8	45	8	30	4	Above sample is not properly weld as per criteria			
4	9	40	16	25	3.5	Above sample is not properly weld as per criteria			
5	7	35	10	20	4.5	7,740	0.890	0.970	0.103
6	6	30	14	25	4	11.400	4.140	4.290	1.152
7	10	40	16	20	3.5	Above sample is not properly weld as per criteria			
8	8	50	20	30	4.5	27.540	7.890	9.39	0.367
9	9	45	8	15	3.5	13.520	1.580	1.820	0.180
10	7	40	10	20	4	7.60	1.180	1.320	0.101
11	8	35	12	25	4.5	Above sample is not properly weld as per criteria			
12	7	40	14	30	3.5	13.700	1.700	2.910	0.183
13	10	35	16	20	4	Above sample is not properly weld as per criteria			
14	6	45	18	15	3.5	4.240	0.350	0.610	0.057
15	7	40	20	30	4.5	7.360	0.770	1.870	0.098
16	9	35	8	15	4	10.080	1.330	2.510	0.134
17	8	45	10	20	3.5	Above sample is not properly weld as per criteria			
18	7	40	12	25	4.5	4.840	0.680	0.840	0.065
19	9	35	14	30	4	11.460	1.520	2.550	0.153
20	8	40	16	20	3.5	Above sample is not properly weld as per criteria			
21	10	45	18	15	4	Above sample is not properly weld as per criteria			
22	6	35	20	20	4.5	5.640	0.670	0.810	0.075

After completing the trial experimentation phase, 12 specimens were tested for tensile strength. The results, including the tensile strength and maximum force for each respective specimen, are summarized in the following table

Table 4. 12 Sample Tensile Test report

Sample No.	Welding Current	Squeeze Time	Hold Time	Weld Time	Welding Pressure	Max Force KN	Dipsp.at FM MM	Max.Disp. Mm	Tensile Strength KN/MM2
5	7	35	10	20	4.5	7.74	0.89	0.97	0.103
6	6	30	14	25	4	11.4	4.14	4.29	1.152
8	8	50	20	30	4.5	27.54	7.89	9.39	0.367
9	9	45	8	15	3.5	13.52	1.58	1.82	0.18
10	7	40	10	20	4	7.6	1.18	1.32	0.101
12	7	40	14	30	3.5	13.7	1.7	2.91	0.183

14	6	45	18	15	3.5	4.24	0.35	0.61	0.057
15	7	40	20	30	4.5	7.36	0.77	1.87	0.098
16	9	35	8	15	4	10.08	1.33	2.51	0.134
18	7	40	12	25	4.5	4.84	0.68	0.84	0.065
19	9	35	14	30	4	11.46	1.52	2.55	0.153
22	6	35	20	20	4.5	5.64	0.67	0.81	0.075

Analysis of Tensile Tests
After conducting train tests, specific fragment points for various test parameters were observed. These paramete rs were used to complete many diagrams showing the relationship between the load used and the material's beha vior.
Analyzing the diagrams, it was observed that the highest break load was reached under a specific set of paramet ers. This indicates that certain conditions affect the strength and capacity of the material. This data provides insi ght into material performance and helps you understand the key factors affecting tensile strength.

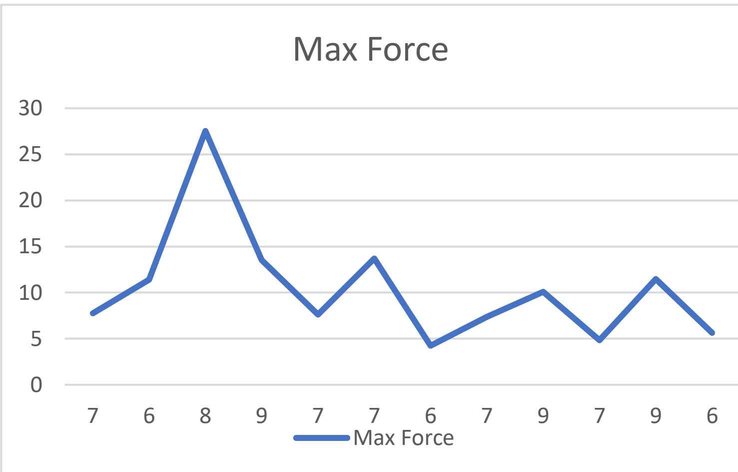


Fig. 06 Welding current and braking load

Fig 06 shows the Welding current VS Braking load . In this graph maximum braking load was observed the 08 no experiment by using 8 KA welding current

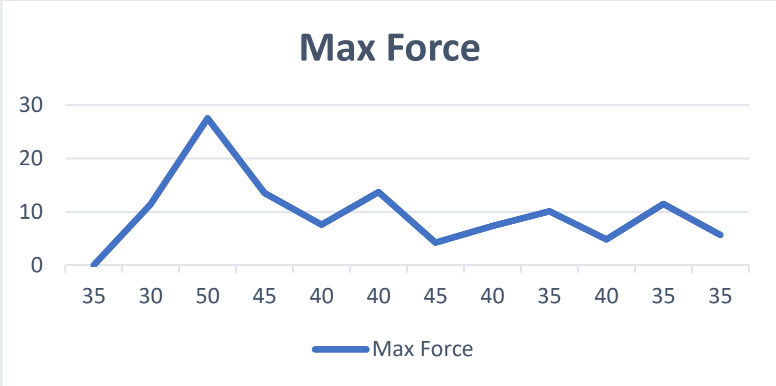


Fig.07 Squeeze time and breaking load

Fig 07 shows the Squeeze time VS Braking load . In this graph maximum braking load was observed the 08 no experiment by using 50 cycle of Squeeze time

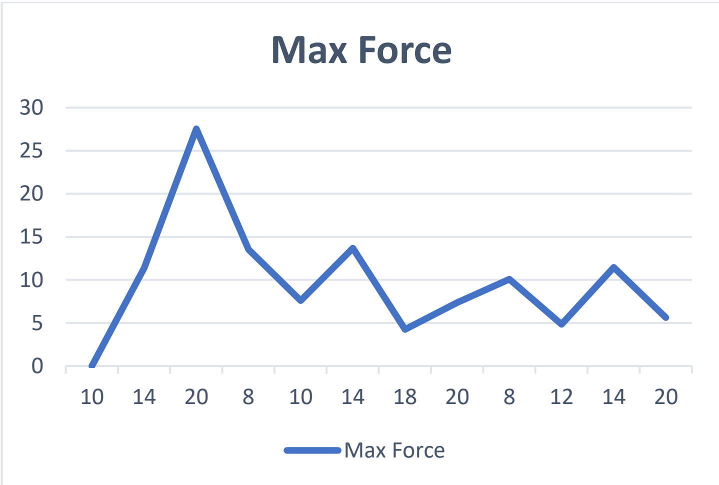


Fig.08 Hold time and breaking load

Fig 08 shows the Hold time VS Braking load . In this graph maximum braking load was observed the 08 no experiment by using 20 cycle of Hold time

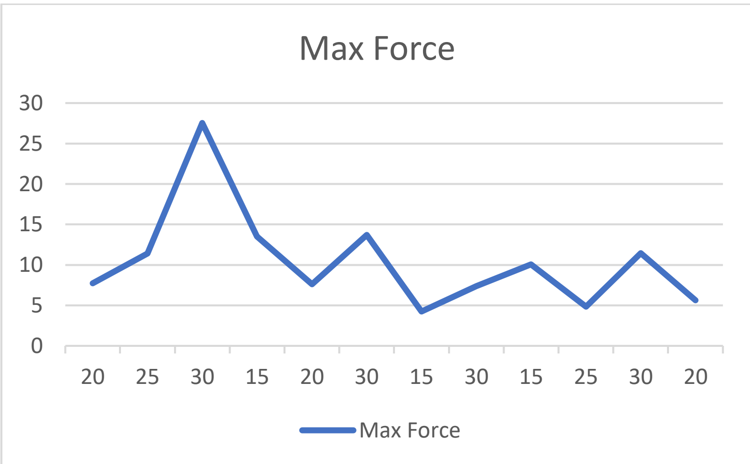


Fig. 09 Weld time and breaking load

Fig 09 shows the Weld time VS Braking load . In this graph maximum braking load was observed the 08 no experiment by using 30 cycle of Weld time

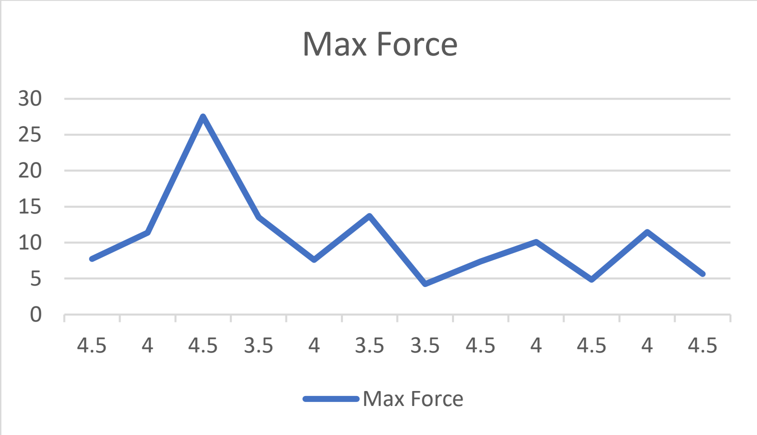


Fig.10 Welding pressure and breaking load

Fig 10 Shows the Welding pressure VS Braking load . In this graph maximum braking load was observed the 08 no experiment by using 4.5 BAR of Welding pressure

Observation of fractures at welded joints

The following image shows the fracture structure observed after the test. These samples highlight the fracture be havior of the basic metal and the corresponding default properties of the weld joint.

Analyzing the fracture area allows you to assess the response of the material under stress and determine the type of failure. Depending on the welding parameters and material properties, fractures can fail brittle, ductile disord er, or a combination of both information. These observations contribute to the assessment of welding quality, str ength, and joint integrity, providing essential knowledge to improve welding techniques.

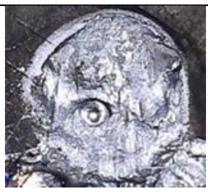
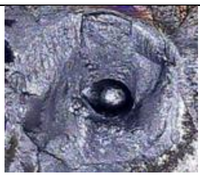
		
Sample No 6	**Sample No 8**	**Sample No 9**
		
Sample No 10	**Sample No 12**	**Sample No 16**

Fig 11. Some sample image analysis

Table 5: Fractography Result of Weld & Observation

Sample No.	Type of fracture	Location of fracture	Fractography Result of Weld & Observation
5	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large excess weld metal, burnt HAZ

6	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large nugget size, weld metal normal
8	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large nugget size, weld metal normal
9	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large nugget size, weld metal normal
10	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large nugget size,
12	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large nugget size, weld metal normal
14	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large excess weld metal,
15	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large excess weld metal, burnt HAZ
16	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large excess weld metal flowing outside the base metal
18	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large nugget size, weld metal normal
19	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large nugget size,
22	Ductile	Weld	Dimple Rupture, shear lips seen, silky texture. Large excess weld metal,

Result and Discussion

During inspection of HSLA 355-based components, it was observed that the upper limit of shock absorbers on Thar vehicles manufactured by Nashik, the Janak industry, showed some of the four-spot welded parts exhibited performance variations. The results showed that the fracture load for the 4-spot welding arrangement was approximately 65 kN. Ideally, four good-quality welded seams should combine strengths or result in more than 110 kN (4 raw 27.54 kN). However, in this case, the observed 65 kN breaking load is lower than expected. However, the results also show that improvements in welding quality, consistency, or process parameters can achieve optimal performance.

Tensiletests were performed on welding connections and fragment points were observed with various parameters. Based on the acquired data, images are applied to analyze variations in cutting loads. It has been observed that the highest fracture load was reached under certain parameter conditions, which was achieved with the optimal combination of factors affecting joint strength. The observed fracture area provided insight into the failure of the weld connection. The highest breakage load has been reached under certain optimized conditions. This indicates that these parameters play a critical role in improving sweat resistance. The type of fracture was dependent on factors such as welding heat input, joint design, and material properties. Understanding these error mechanisms can help improve welding techniques and improve the structural integrity and key capabilities of the weld components.

	
Fig.12 HSLA 355 4 Spot welded parts	Fig.13 HSLA 355 4 Spot Tensile test welded part

Conclusion

This study investigated the effects of the most important resistive spot welding current, compression time, retent ion time, welding time and welding pressure on the tensile strength of HSLA 355 steel connections. A total of 2 2 experimental experiments were conducted using a pneumatically controlled resistance welding machine, with Boxbankein designs used for optimization. The results showed that the connection strength had a significant imp act with optimized parameters (6 ka welding current, hold time of 14 ms, welding time of 25 ms, welding time, 4 kN welding pressure, and optimized parameters (optimized current, hold time of 14 ms, welding time of 25 ms , max mechanical strength of application. Implementation of such technologies has contributed to the developme nt of reliable, stronger welding compounds in a variety of industrial applications.

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