SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V12I3P101

Volume 12 Issue 3, 1-27, March 2025

Review Article

Recent Status of Research and Developments in Resistance Spot Welding

Ramakant Choudhari[1], Amit Adhaye[1], Vishal Sulakhe[1], Ritesh Fegade[2]

[1]*Department of Mechanical Engineering, Sandip University, Nashik, Maharashtra, India.*
[2]*Department of Mechanical Engineering, PGMCOE, Wagholi, Pune, Maharashtra, India.*

[2]*Corresponding Author : riteshfegade@gmail.com*

Received: 03 January 2025 Revised: 02 February 2025 Accepted: 01 March 2025 Published: 29 March 2025

Abstract *- Resistance Spot Welding (RSW) continues to be a cornerstone of modern manufacturing, predominantly in the automobile industry. This comprehensive review examines recent advancements in RSW technology, focusing on recent developments in RSW. Integrating advanced materials, such as cutting-edge High-Strength Steel (HSS) and lightweight alloys, has necessitated significant innovations in welding processes and quality control. This review critically analyzes progress in joining dissimilar materials, optimizing process parameters, and understanding complex microstructural evolution in weld zones. Emerging technologies, including machine learning-based predictive models and real-time monitoring systems, are reshaping quality assurance in RSW. By synthesizing findings from over 100 recent studies, this article provides a holistic view of the current state of RSW technology and identifies key areas for future research. The ongoing evolution of RSW underscores its enduring relevance in an era of rapid technological change and increasingly demanding manufacturing requirements.*

Keywords *- Resistance Spot Welding (RSW), Dissimilar materials joining, Process optimization, Process parameters, Microstructure, High-strength steels, Hybrid joints.*

1. Introduction

Resistance Spot Welding (RSW) has undergone substantial advancements throughout time, making it a highly prevalent approach for metal joining in diverse industries owing to its effectiveness, rapidity, and dependability [1]. These techniques utilize electrical resistance to produce heat and then join metal sheets together by fusion [2]. With the progression of technology, the techniques used in RSW have gotten more advanced, resulting in enhanced welding precision and broader utilization.

The history and introduction of RSW reveal a rich tapestry of research endeavors focused on comprehending and enhancing this commonly used metal joining method. A chronological exploration of key studies provides insights into the evolution of RSW techniques and their diverse applications across different materials. RSW, a prominent method in various industries, including automotive and manufacturing, has undergone significant advancements [3].

1.1. Principal and Working

The RSW process is extensively applied in the industry to connect sheets in the automotive and aerospace sectors [6]. RSW has many advantages over other welding processes, such as inexpensive equipment setup and easy control over the process, and it can also be performed by unskilled workers [5]. Due to these advantages, it is widely used in the manufacturing process. Spot, projection and seam welding are three resistance welding processes in which the metal gets fused at the point where force and current are applied to the workpiece [7]. A common problem manufacturers face is the deterioration of weld quality and strength due to improper selection of levels of processing parameters [8].

Hence, establishing the relationship between the strength and quality of the weld and the levels of processing parameters is very important in industrial applications. In RSW, heat is used to fuse the work parts of metal. Current flows across the two workpieces due to which electrical resistance is set up and heat is generated.

In RSW, two metalwork parts are joined together by applying electric current and pressure in the zone to be welded. The difference between RSW and arc welding is that RSW doesn't need any filler metal addition to the weld area.

Spot welding is influenced by four key factors:

a. The amount of current passing through the workpiece.
b. The pressure applied by the electrodes on the workpiece.
c. The duration of current flow through the workpiece.
d. The contact area of the electrode tip with the workpiece.

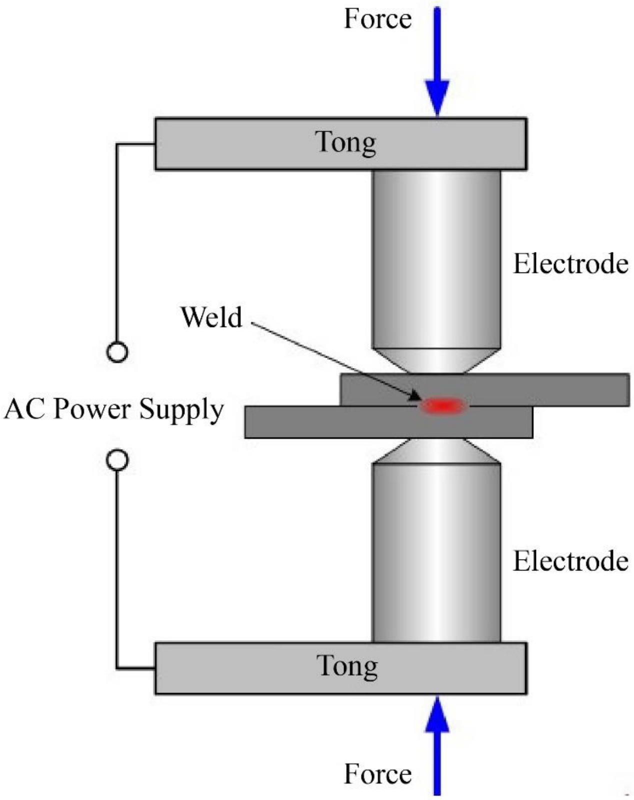

Fig. 1 Resistance Spot Welding (RSW) working

During the welding process, electric current is directed through the electrodes and subsequently transmitted to the workpieces. The leg pedal is employed to apply force, effectively compressing the electrodes onto the workpieces. For optimal weld strength and quality, it is essential to apply a precise amount of pressure to the workpieces.

The electric current flows from the electrodes to the workpieces throughout the welding operation. The leg pedal delivers the necessary welding force, and it is critical to apply the correct pressure to the workpieces to ensure high-quality welds. The electric current travels from the electrode tips to the designated metal workpieces during welding, facilitating their fusion. Figure 1 shows the working of RSW.

The resistance of the base metal to electrical current flow generates heat, which is confined to the area where the electrode tip contacts the weld area. Heat is produced while the welding force is maintained. During the holding stage, where pressure is still applied, the current is switched off, allowing the nugget to cool under pressure.

The heat generated in spot welding primarily depends on the electric current, application duration, and the material's electrical resistance between the electrodes. The amount of heat produced is a function of current, time, and resistance. According to Joule's law, the following equation expresses the heat generated in Resistance Spot Welding (RSW).

$$H = I^2 \times R \times t \tag{1}$$

Where,
H = Heat generated in joules
I = Current (in amperes)
R = Resistance (in ohms)
t = Time to current flow (in seconds)

1.2. Overview of RSW Techniques and Applications

Conventional RSW uses copper electrodes to compress two or more metal sheets and pass an electric current through them. The resistance to the current flow generates heat, resulting in localized melting and fusion of the metal sheets. Due to its cost-effectiveness and speed, these methods are widely used in the automotive industry to join car body panels and fabricate chassis components.

In the aerospace industry, it is utilized to assemble lightweight sheet metal components in aircraft. In manufacturing plants, RSW is commonly applied in the fabrication of appliances, enclosures, metal constructions, and the production of metal containers.

Advanced RSW techniques, such as Pulsed RSW, use pulsed current during welding to allow greater control over heat generation and minimize thermal distortion. This method is ideal for joining lightweight materials like aluminium and high-strength alloys used in modern automotive designs. High-frequency RSW operates the welding current at a higher frequency, resulting in quicker energy transfer and reduced heat-affected zones. It is particularly useful for producing thin-walled components with minimal thermal distortion in the electronics industry.

Micro RSW uses highly focused welding electrodes for precise and controlled welding in micro-scale applications, such as the assembly of miniature components like sensors and electronic devices in the electronics and microelectronics sectors.

Robotically controlled RSW integrates robotic arms with RSW systems to enhance precision and enable complex welding patterns. This approach is applied in automated manufacturing processes to ensure uniformity and efficiency. Specialized RSW applications include joining dissimilar materials like steel and aluminium, which expands the use of hybrid material structures in various industries. Methods have also been developed to adapt to the unique properties of Advanced High-Strength Steels (AHSS) for contemporary lightweight and high-strength applications.

Techniques to control the microstructure of the welded junction help achieve specific mechanical properties and improve overall performance. Additionally, integrating online monitoring and quality control systems is essential for real-time quality control in industries prioritising precision and reliability.

This review critically analyzes progress in joining dissimilar materials, optimizing process parameters, and understanding complex microstructural evolution in weld zones. Emerging technologies, including machine learning-based predictive models and real-time monitoring systems, are reshaping quality assurance in RSW. Novel hybrid techniques, such as laser-assisted and ultrasonic-assisted RSW, demonstrate promising results in overcoming traditional limitations.

Persistent challenges, including liquid metal embrittlement in zinc-coated steels, are examined alongside proposed solutions. The review also explores the role of RSW in automotive lightweighting strategies and the production of electric vehicles [4, 5]. Overall, the studies demonstrate that the historical progression of RSW research has been consistent in the effort to comprehend, enhance, and introduce new ideas in the field of metal joining techniques.

The works offered here provide a complete grasp of the problems and opportunities in the subject of RSW by exploring various materials, welding processes, and failure assessments.

2. Literature Review

RSW technologies have expanded to cater to the needs of various industries, including classic applications in automotive and industrial sectors to sophisticated procedures for joining diverse materials and microelectronics. The advancing methods remain crucial in contemporary manufacturing, aiding in creating robust, effective, and top-notch metal structures for various uses.

The literature on RSW covers a wide range of studies that investigate its uses and mechanics. Table 1 shows a detailed summary of recent research carried out in the field of RSW.

2.1. Inferences from the Literature

The literature study identifies various prominent research subjects and areas of interest in the field of RSW, with a specific emphasis on techniques, materials and related methods. The research interferences that have been identified can be summarised as follows:

2.1.1. Process Optimization and Parameter Control

Several studies have highlighted the significance of optimizing process parameters in RSW. These investigations explored the influence of many aspects on the quality of welds, such as nugget size, mechanical performance, and failure modes. The objective is to improve the effectiveness and dependability of the welding procedure by implementing accurate control and optimisation.

2.1.2. Dissimilar Material Joining

A substantial body of literature specifically examines the difficulties and progress made in the process of combining different elements.

This research enhances the comprehension of the behaviour of dissimilar material welds by investigating techniques such as ultrasonic spot-welding and hybrid welding processes. They also provide crucial insights into these connections' microstructural characteristics and mechanical properties.

2.1.3. Quality Inspection and Monitoring

Several studies have explored integrating machine learning and online inspection techniques to ensure the quality of RSW.

The objective of these initiatives is to provide reliable techniques for continuously monitoring and ensuring the quality of products on manufacturing lines, hence minimising flaws and improving total productivity.

2.1.4. Hybrid Welding Techniques

The literature survey encompasses investigations on hybrid welding methods, which involve the integration of RSW with other techniques, such as laser welding (Li et al., 2022) and ultrasonic spot welding (Rajalingam et al., 2023). These investigations examine the advantages of hybrid procedures, with the goal of attaining higher weld characteristics and tackling the difficulties linked to conventional welding methods.

2.1.5. Microstructure and Mechanical Property Analysis

Several studies have investigated the microstructural features and mechanical behaviour of welds. Comprehending the relationship between process parameters, material qualities, and the final microstructure is essential for accurately predicting and enhancing the performance of welded joints.

Overall, these research interferences collectively contribute to enhancing the comprehension of welding processes, optimizing their parameters, and broadening their applications to satisfy the increasing requirements of diverse industries.

Table 2 summarises the various aspects of the studies carried out on RSW, and Table 3 shows the types of investigations carried out on RSW.

Table 1. Recent research on RSW with a summary of investigations

Author (year)	Investigations	Materials	Techniques	Results	Scope and Gap
Aghajani et al. (2023) [9]	Microstructure engineering of fusion zone	Martensitic stainless steels	RSW with Ni interlayer	Role of Ni interlayer thickness	Focused on specific steel type; gap in other materials.
Alden et al. (2022) [1]	Joints properties	Aluminium and steel	RSW	Hybrid joints Characteristics	Limited to specific material combinations.
Al-hamdani (2022) [10]	Effect of interlayer on joint properties	Galvanized steel sheets	RSW with Al-Cu foil interlayer	Impact on failure modes and mechanical properties	Specific focus on interlayer; gap in direct joining.
Amini-Chelak et al. (2023) [11]	Weldability of advanced HSS	Fe66Cr16.5Ni14.1Si3.4 steel	RSW	Optimization of welding parameters	Limited to specific steel composition.
Ariyanto et al. (2023) [12]	Optimization of RSW parameters	Dissimilar materials	RSW	Review of optimization techniques	Broad scope: the gap in specific material combinations.
Asati et al. (2022) [13]	Comparison of joining techniques	Dissimilar galvanized steel sheets	Self-piercing riveting, RSW	Comparative analysis of joining methods	Limited to automotive-grade materials.
Bachchhav et al.(2023) [14]	Wear performance of electrode materials	Cu–Cd, Cu–Be, Cu–Cr–Zr	RSW	Wear characteristics of different electrodes	Focused on electrode materials; gap in weld quality.
Badkoobeh et al. (2023) [15]	Phase evolutions and joint performance	AISI 430 and AISI 321 steels	RSW	Tensile-shear performance of dissimilar welds	Limited to specific steel combinations.
Baek et al. (2022) [2]	Fatigue properties of lap joints	Aluminum/HSS	Resistance element welding	Microstructural and geometrical influence on fatigue	Focused on lightweight vehicles; gap in other applications.
Bagali et al. (2022) [16]	Optimization of RSW parameters	Low-carbon steel sheet	RSW	Achieving desired spot size in shop floor environment	Limited to specific steel types and applications.
Balsaraf et al. (2022) [17]	Mechanical characterization and optimization	Multigrade AHSS	RSW	Review of characterization and optimization techniques	Broad scope; gap in specific grade comparisons.
Bamberg et al. (2022) [6]	Improvement of RSW for Al-Mg-Si alloys	Al-Mg-Si alloys	RSW with cladding technology	Optical and mechanical characterization	Specific focus on aluminum alloys.
Başer (2023) [4]	RSW of third-generation automotive steels	Zn-coated steels	Mid-frequency direct current RSW	Welding performance with new technology	Limited to specific steel type and coating.
Betiku et al.	Improving	Press-hardened steel	RSW with in-situ	Enhanced	Focused on

(2022, 2023) [18, 19]	mechanical performance and optimization of post-weld performance		grain refinement	mechanical properties	specific steel type; gap in other materials.
Bi et al. (2022) [20]	Joint formation mechanism	AA 5754 aluminum alloy	Resistance butt spot welding	Performance analysis of butt spot welding	Limited to specific aluminum alloy.
Butsykin et al. (2023) [21]	Reliability of RSW control	Not specified	RSW with dynamic resistance monitoring	Evaluation of on-line monitoring techniques	Focused on control method; gap in material-specific applications.
Chabok et al. (2022) [22]	Fracture behavior	Advanced HSS	RSW	New insights into fracture behavior	Focused on specific steel type; gap in other materials.
Chanh et al. (2022) [23]	3D crack propagation	Martensitic stainless steel	RSW	Experimental determination of crack propagation	Limited to specific steel types.
Chen et al. (2022a) [24]	Nugget size prediction	Al–Si-coated press-hardened steel	RSW	Critical nugget size prediction model	Specific to coated steel, gaps in uncoated materials.
Chen et al. (2022b) [25]	Post-weld tempering	Q&P1180 steel	RSW with tempering pulse	Effect on microstructure and mechanical properties	Limited to specific steel grade.
Chen et al. (2022c) [26]	Shearing strength	Dissimilar steel plates	RSW	Effect of welding current and time on joint strength	Focused on dissimilar steel gaps in similar materials.
Chen et al. (2023) [27]	Joint strength enhancement	NiTi/304 stainless steel	Ultrasonic spot welding	Investigation of interlayer effects	Focused on specific material combinations.
Chudasama et al. (2022) [5]	Welding parameter effects	AISI 2205 DSS	RSW	Performance of spot welded joints	Limited to specific steel grade and automotive applications.
Dahmene et al. (2022) [28]	Nondestructive testing	Not specified	RSW	Monitoring of cracks in spot welds	Focused on testing methods; gap in prevention strategies.
Dai et al. (2022) [29]	Online quality inspection	Not specified	RSW	Quality inspection for automotive production	Focused on automotive application; gap in other industries.
Das et al. (2023) [30]	Use of graphene interlayer	CR210 steel	RSW with graphene interlayer	Microstructure and mechanical behavior	Novel approach with specific material; gap in other interlayers.
Delgado-Pamanes et al. (2022) [31]	RSW of galvanized HSLA steel	Galvanized HSLA steel sheets	RSW	Experimental and numerical study	Limited to specific steel types.

Deng et al. (2022) [32]	Asymmetric nugget growth	Aluminum	RSW with multi-ring domed electrodes	Experimental study of nugget growth	Focused on aluminum; gap in other materials.
Deshmukh & Kharche (2023) [7]	Processing conditions influence	SS 316L sheet	RSW	Tensile strength and failure pattern	Limited to specific stainless steel grades.
Ding et al. (2022) [33]	Tensile shear strength enhancement	TWIP steel	RSW, numerical and experimental methods	Improvement strategies for TWIP steel	Focused on specific steel types.
Dong et al. (2023) [34]	Internal oxidation layer role	Zn-coated AHSS	RSW	Effect on liquid metal embrittlement	Focused on coated AHSS.
Dong et al. (2022a) [35]	Zn penetration and grain boundary interaction	QP980 steel	RSW	Coupled interaction study	Limited to specific steel grade.
Dong et al. (2022b) [36]	Liquid metal embrittlement cracks	Advanced HSS	RSW	Determination of crack existence	Specific to AHSS, gaps in other steel types.
Doruk et al. (2022) [37]	Mechanical and fatigue behavior	Dual-phase and TWIP steel	RSW	Joint performance comparison	Focused on specific steel combinations.
Ebrahimpour et al. (2023) [38]	Welding parameters effect	TRIP steel	RSW, FEM analysis	Nugget zone and HAZ geometry	Limited to TRIP steel.
Elitas & Erden (2023) [39]	Welding parameters effect	Non-alloyed steel (powder metallurgy)	RSW	Tensile properties and failure modes	Limited to specific steel type; gap in alloyed steels.
Elitas (2023) [40]	Welding parameters effects	DC01 steel	RSW	Tensile properties and failure modes	Focused on specific steel grade.
Eriksson (2023) [41]	Joining dissimilar materials	Ultra HSSand Aluminium	Resistance Welding	Not specified	Focused on specific material combinations.
Fakhri et al. (2022) [42]	Comparative study	Not specified	Spot welding	Mechanical properties comparison	Broad scope; gap in material-specific analysis.
Ganjabi et al. (2023) [43]	Defects effect on strength	Not specified	Spot welding	Static and cyclic loading performance	Focused on defects; gap in defect prevention.
Ghanbari et al. (2022) [8]	Fatigue behavior	Ferrite-martensite dual-phase steel, hybrid joints	Spot welding	Effects of welding parameters	Limited to specific steel types.
Shamsolhodaei et al. (2022) [44]	Microstructural evolution	NiTi shape memory alloy	RSW	Microstructure and mechanical properties	Focused on specific alloy; gap in other memory alloys.
Ghatei-Kalashami et al. (2022b) [45]	Failure behavior	Advanced HSS	RSW	Surface condition with microstructure	Limited to AHSS; gap in other steel types.
Googarchin et al. (2022) [46]	Plastic deformation effects	Aluminum	RSW	Mechanical properties of automotive joints	Focused on automotive applications.
Guo et al.	Electrode	Mg/steel	RSW	Modeling of	Limited to

(2022) [47]	morphology effect			electrode effects	Mg/steel combination.
Hagen et al. (2023) [48]	Dissimilar material joining	Not specified	RSW with cold gas sprayed in inlayer	Not specified	Novel approach; gap in traditional methods.
Hassan & Lafta (2023) [49]	Electrode geometry and pre-heating	Not specified	RSW	Welding strength	Focused on specific parameters; gap in material effects.
Hassoni et al. (2022) [50]	Welding parameters effect	316L	RSW	Mechanical properties and corrosion resistance	Limited to specific steel grade.
He et al. (2022) [51]	Quality prediction and optimization	Not specified	RSW, Machine Learning	Predictive modeling	Broad scope; gap in material-specific models.
He et al. (2023) [52]	Hybrid joining	HSS and aluminum alloy	Rivet plug laser welding	Not specified	Novel technique; gap in traditional methods.
Hendrawan et al. (2023) [53]	Zinc powder grain size effect	Dissimilar metals	RSW	Not specified	Focused on specific parameters; gap in other factors.
Iyota et al. (2023a) [54]	Dissimilar joining	HSS and aluminum alloy	RSW with shaped electrodes	Not specified	Limited to specific material combinations.
Iyota et al. (2023b) [55]	Convection in the molten zone	Fe/Al	RSW	Convection behavior	Focused on the specific phenomenon: a gap in the overall process.
Jafari Vardanjani (2022) [56]	Comparative study	Not specified	Resistance spot brazing vs RSW	Technical aspects comparison	Broad scope; gap in material-specific analysis.
Janardhan et al. (2022a) [57]	Failure behavior	Automotive steel sheets	Spot welding	Failure characteristics	Focused on automotive steels.
Janardhan et al. (2022b) [58]	Failure mechanism	DP600 steel	RSW	High cycle fatigue behavior	Limited to specific steel grade.
Janardhan et al. (2023) [59]	Work hardening influence	Dual-phase steel	RSW	Tensile and fatigue behavior	Limited to specific steel types.
Ji et al. (2022) [60]	Welding temperature field and residual stresses	Corrugated steel web girders	Not specified	Not provided in the abstract	Focus on structural aspects of welding; gap in detailed temperature and stress analysis.
Jia et al. (2023) [61]	Microstructure and tensile shear properties	9Cr oxide dispersion strengthened steel	RSW	Not provided in the abstract	Investigate specialized steel gaps in comparison with other steel types.
Jin et al. (2022) [62]	Liquid Metal Embrittlement	Zinc-coated steels	RSW	Effect of process	Focuses on a specific welding

	(LME) cracking			parameters and nugget growth rate on LME cracking	issue; gap in solutions to prevent LME.
Jing et al. (2022) [63]	Improving mechanical properties	Q&P980 steel	Multi-pulse RSW	Improved mechanical properties through microstructure tailoring	Explores advanced welding technique; gap in applicability to other steel types.
Kar et al. (2023) [64]	Effect of plate placement on nugget shape	Dissimilar thickness automotive steel thin sheets	RSW	Influence of plate placement on weld quality	Addresses practical welding issues, such as the gap in optimizing for various thickness combinations.
Kumar et al. (2022) [65]	Joining ultra-thin foil to thick steel	Inconel 718 and 410 steel	Flexible laser spot welding	A potential substitute for RSW	Explores alternative welding method; gap in large-scale applicability.
Li et al. (2022) [66]	Hot cracking phenomena	6061/7075 dissimilar aluminum alloys	RSW	Numerical and experimental study results	Focuses on aluminum alloys; gap in preventing hot cracking.
Li et al. (2022) [67]	Hybrid welding of dissimilar materials	Aluminum to steel	Hybrid resistance-laser spot welding	Microstructure and mechanical properties analysis	Investigate innovative welding techniques gaps in optimization for various material combinations.
Liu et al. (2023) [68]	Mechanical properties and failure mechanism	Medium manganese TRIP steel/DP590 steel	RSW	Not provided in the abstract	Examines dissimilar steel welding; gap in understanding long-term performance.
Manladan et al. (2023) [69]	Effect of paint baking on joint properties	30MnB5 hot-stamped steel	RSW	Impact on halo ring and mechanical behavior	Considers post-welding processes; gap in effects on other steel types.
Martín & De Tiedra (2022) [70]	Control and improvement of quality	Not specified	RSW	Advances in quality control	Review of quality improvement methods; gap in implementation strategies.
Mathiszik et al. (2022) [71]	Nugget microstructure characterization	Not specified	RSW, Magnetic characterization	Not provided in the abstract	Novel approach to microstructure analysis; gap in correlation with mechanical properties.
Midawi et al. (2022) [72]	Local mechanical	Third-generation advanced HSS	RSW, Novel measurement	New method for measuring	It focuses on advanced steels,

	properties measurement		technique	local properties	but there is a gap in the application of it to other materials.
Midhun et al. (2022) [73]	Dissimilar metal welding	AISI 304 and AISI 202	RSW	Not provided in the abstract	Investigate specific steel combinations; gap in optimizing parameters.
Mirmahdi et al. (2023) [74]	Defect evaluation	Not specified	Ultrasonic testing in spot welding	Review of experimental and simulation results	Comprehensive review; gap in standardization of testing methods.
Nadimi et al. (2023) [75]	Fusion zone hardness understanding	Advanced HSSs	RSW, Data-driven modeling	Insights into strengthening mechanisms	Focuses on hardness; gap in relating to overall joint performance.
Nomura et al. (2023) [76]	Non-contact nugget diameter measurement	Not specified	RSW, Laser ultrasonic technique	Development of a new measurement method	Innovative inspection technique; gap in industrial application.
Pan et al. (2022) [77]	Intermetallic compound formation	Aluminum/steel	RSW	Understanding of formation mechanisms	Focuses on dissimilar metal joining; gap in controlling IMC formation.
Panza et al. (2022, 2023) [78, 79]	Electrode wear prediction	Not specified	RSW, Machine learning	Development of a prediction tool	Addresses practical issue: the gap in real-time implementation.
Pawar et al. (2023) [80]	Effect of welding current on joint properties	340BH steel	RSW	Microstructural evolution and lap-shear performance	Specific to one steel grade; gap in broader application.
Piotr & Judyta (2023) [81]	Lap joint analysis	Grade 2 Titanium and Grade 5 Titanium alloy	RSW	Numerical and experimental analysis results	It focuses on titanium alloys and the gap in comparison with other joining methods.
Pittner & Rethmeier (2022) [82]	Life cycle assessment	Not specified	RSW, Laser beam welding	Comparison of environmental impacts	Focuses on sustainability; gap in comprehensive process comparison.
Prabhakaran et al. (2023a,b) [83, 84]	Weld strength and microstructure	AISI 347 and AISI 2205 stainless steels	RSW	Analysis of joint properties	Examines specific steel combinations; gap in optimizing for other alloys.
Prasetya & Hendrawan (2023) [85]	Nugget analysis and tensile shear load	Dissimilar metals	RSW with zinc powder	Not provided in the abstract	Novel approach using zinc powder; gap in understanding

					long-term effects.
Qiu et al. (2023) [86]	Joint characterization	Aluminum alloy and mild steel	RSW with composite electrodes	Analysis of joint properties	Addresses dissimilar metal joining; gap in optimizing electrode composition.
Rajak et al. (2023) [87]	Comparison of welding techniques	Dual-phase 590 (DP 590) steel	TIG-spot welding, RSW	Processing-microstructure-property correlation	Compared to welding methods, there is a gap in applicability to other steel grades.
Rajalingam et al. (2023) [88]	Tensile shear fracture load, HAZ softening	DP-1000 steel	RSW	Analysis of joint properties and microstructure	It focuses on HSS, which is a gap in fatigue performance.
Rajarajan et al. (2022a,b,c) [89, 90, 91]	Microstructure and mechanical properties	Advanced high strength dual phase steel	RSW	Effect of welding parameters on joint quality	A comprehensive study on specific steel; gap in transferability to other materials.
Ramachandran et al. (2022) [92]	Improving mechanical performance	Q&P 980 steel	RSW	Control of halo ring formation	Focuses on specific steel grade; gap in broader application.
Rao et al. (2022) [93]	Modelling and optimization	DP590 steel sheets	RSW, RSM-GA technique	Optimization of weld responses	Applies advanced modeling; gap in real-time process control.
Rdzawski et al. (2023) [94]	Welding cap degradation	Not specified	RSW	Changes in microstructure and properties of welding caps	Addresses practical issue: a gap in cap material optimization.
Reddy Gillela et al. (2023) [95]	Contact conditions, dynamic resistance, nugget size	AISI 1008 steel sheets	RSW, Numerical study	Insights into the weld formation process	Focus on specific steel; gap in experimental validation.
Ren et al. (2022) [96]	Post-weld cold working for fatigue strength improvement	Advanced HSS	RSW, Post-weld treatment	Enhanced fatigue strength	Novel approach; gap in long-term effects.
Ren et al. (2023) [97]	Process to residual stress modeling	DP980 steel	RSW, Numerical modeling	Comprehensive process-structure-property relationship	Limited to one steel grade; gap in other materials.
Reza Kashyzadeh et al. (2022) [98]	Shunting effect in multi-sheet welding	Three-steel sheets	RSW, Numerical study	Understanding of shunting in complex setups	Specific to three-sheet setup; gap in other configurations.
Reza Kashyzadeh et	Fatigue life analysis	Not specified	RSW, Numerical analysis	Effects of sheet thickness and	Comprehensive analysis; gap in

al. (2023) [99]	considering residual stress			electrode geometry	experimental validation.
Russell et al. (2023) [100]	Data-driven modeling for weld quality prediction	Not specified	RSW, Machine learning	Comparison of modeling techniques	Focus on prediction; gap in real-time application.
Sadeghian et al. (2022) [101]	Microstructure prediction in dissimilar welding	Stainless steel to carbon steel	RSW, Simulation	Microstructure evolution insights	Limited to specific material pair; gap in mechanical properties.
Sammaiah et al. (year not provided) [102]	Effect of weld parameters	AISI C1010 cold rolled carbon steel	Direct RSW	Effect of weld parameters	Focus on automotive applications; gap in a comprehensive parameter study.
Sar et al. (2022) [103]	Joining of dissimilar metals	Aluminum and copper	RSW	Influence of welding parameters	Addresses challenging material combinations and gaps in joint durability.
Sarmast-Ghahfarokhi et al. (2022a,b) [104, 105]	Failure mechanism and mechanical properties	Third-generation medium-Mn steel	RSW	Behavior under static and quasi-static loading	A comprehensive study on specific steel; gap in dynamic loading conditions.
Schmolke et al. (2023) [3]	Seam leak tightness in welding of HSSs	HSSs	Laser beam welding, RSW bonding	Seam leak tightness in welding of HSSs	Focus on leak tightness; gap in comprehensive performance evaluation.
Sexton & Doolan (2023) [106]	Effect of electrode misalignment on spot weld quality	Not specified	RSW	Effect of electrode misalignment on spot weld quality	Addresses a specific welding parameter; gap in holistic parameter optimization.
Shah (2022) [107]	Ultrasonically assisted RSW	Lightweight metal alloys	Ultrasonic-assisted RSW	Ultrasonically assisted RSW	Novel technique application; gap in comparison with conventional methods.
Devendranath Ramkumar et al. (2019) [108]	Laser Welding	Inconel 718 and AISI 416	Single pass using keyhole mode CO_2 laser welding process	Successfully joined ultra-thin foil to thick steel	The fusion zone microstructure attested the absence of solidification cracks and/or porosity.
Sharma et al. (2022) [109]	Improvement of microstructural and mechanical properties	Aluminum 6063 alloy	RSW	Improved properties for aerospace application	Focused on specific alloy; gap in applicability to other aerospace materials.
Shi et al. (2023)	Fatigue	Maraging steel	RSW	Fatigue	Combines additive

[110]	properties of spot-welded maraging steel	produced by selective laser melting		properties	manufacturing with welding; gap in process optimization.
Soomro et al. (2022) [111]	Review of advances in RSW	Automotive sheet steels	Various emerging methods	Improved joint mechanical performance	Comprehensive review; gap in practical implementation of emerging methods.
Taghavi & Pouranvari (2023) [112]	Dissimilar welding of immiscible alloys	Iron and copper alloy system	RSW with spinodal liquid phase separation	Enabled welding of immiscible alloys	Novel approach for dissimilar welding; gap in process control and repeatability.
Taufiqurrahman et al. (2022) [113]	Effect of aluminum interlayer on dissimilar welding	Stainless steel 316L, Ti6Al4V titanium alloy	RSW with aluminum interlayer	Effect of aluminum interlayer on dissimilar welding	Addresses challenging dissimilar joints; gap in long-term joint stability.
Tian et al. (2022) [114]	Microhardness and fatigue life investigation	Quenching and partitioning 1180 steel	Spot welding	Microhardness and fatigue life investigation	Focus on advanced HSS; gap in comparison with other joining methods.
Tolton et al. (2023) [115]	RSW failure in tailor hot stamped assemblies	Not specified	RSW, Hot stamping	RSWfailure in tailor hot stamped assemblies	Focus on failure mechanisms in hot stamped assemblies; gap in prevention strategies.
Tuncel et al. (2023) [116]	Parametric study on weld zone shape	22MnB5 steel	RSW	Parametric study on weld zone shape	Emphasis on weld zone geometry; gap in relating shape to mechanical properties.
Tyagi et al. (2022) [117]	Optimization of robot spot welding parameters	Low carbon steel JSC 590RN	Robot spot welding	Optimization of robot spot welding parameters	Robotic welding optimization; gap in comparison with manual welding.
Uematsu et al. (2023) [118]	Fatigue behavior with different electrode tip diameters	Steel sheets	RSW	Fatigue behavior with different electrode tip diameters	Effect of electrode geometry on fatigue; gap in optimizing electrode design.
van der Aa & Rana (2023) [119]	Minimizing liquid metal embrittlement cracking	Zinc-coated medium manganese steel	RSW, Hot forming	Optimization of hot-forming temperature	Addresses specific material issues, such as the gap in applicability to other coated steels.
Van Nhat Nguyen (2022) [120]	Quality of dissimilar joint	Aluminum alloy and low-carbon steel	RSW	Quality of dissimilar joint	Dissimilar metal joining; gap in long-term joint stability.

Vignesh (2022) [121]	Predicting parametric influence on tensile shear load	Not specified	RSW	Prediction model for tensile shear load	Focuses on load prediction; gap in comprehensive joint quality prediction.
Wang et al. (2022) [122]	Microstructure and shearing strength of dissimilar joint	Stainless steel and low-carbon steel	RSW	Not specified in the given text	Dissimilar steel joining; gap in corrosion resistance of the joint.
Wang et al. (2022) [123]	Numerical prediction of weld failure	Not specified	RSW	Integrated approach for failure prediction	Computational modeling; gap in experimental validation.
Wang et al. (2022) [124]	Microstructures and fatigue behavior of the dissimilar joint	Aluminum and steel	RSW	Microstructures and fatigue behavior of the dissimilar joint	Al/steel joining with focus on fatigue; gap in improving fatigue life.
Wang et al. (2022) [125]	Zinc-induced liquid metal embrittlement	Advanced HSS	RSW	Zinc-induced liquid metal embrittlement	Specific material degradation mechanism; gap in prevention methods.
Wei et al. (2022) [126]	Similar and dissimilar weldability	Q&P980 and TWIP1180 steels	RSW	Similar and dissimilar weldability	Weldability of advanced steels; gap in optimizing parameters for these specific alloys.
Wippermann et al. (2023) [127]	Thermal influence of spot welding on nearby overmolded joint	Thermoplastic-metal	RSW	Thermal influence of spot welding on nearby overmolded joint	Interaction between welding and overmolding; gap in optimizing process sequence.
Xiao et al. (2022) [128]	Dissimilar welding in keyhole mode	Aluminum alloy to steel	Laser spot welding	Dissimilar welding in keyhole mode	Novel approach for dissimilar welding; gap in comparison with other modes.
Xu & Fang (2023) [129]	New joining method for FRP-steel	Thermoplastic FRP, steel	Resistance insert spot welding	Proposed new joining method	Innovative technique; gap in long-term performance and scalability.
Xu et al. (2023) [130]	Effects of magnetic fields in welding	Various	Arc, laser, and RSW	Review of magnetic field effects	Comprehensive review; gap in practical implementation strategies.
Yaghoobi et al. (2022) [131]	Welding of high-strength and nano/ultrafine-	DP steel, IF steel	RSW	Welding of high-strength and nano/ultrafine-	Focus on advanced materials; gap in optimizing for these specific

	grained steels			grained steels	steels.
Yang et al. (2022) [132]	Dissimilar aluminum alloy joining	2195/5A06 aluminum alloys	RSW	Microstructure and mechanical properties analyzed	Specific alloy combination; gap in fatigue and corrosion performance.
Yao et al. (2023) [133]	Local mechanical characterization and fracture prediction	Advanced HSS	RSW	Developed prediction model	Focus on fracture prediction; gap in a real-time monitoring application.
Yu et al. (2023) [134]	Ultrasonic seam-assisted welding with interlayer	Titanium, steel, copper interlayer	Ultrasonic seam-assisted RSW	Interfacial evolution and mechanical properties studied	Novel technique for dissimilar metals; gap in process parameter optimization.
Yun et al. (2022) [135]	Improving weldability of coated steel	Al-Fe-alloy-coated HPF steel	RSW	Improved weldability	Specific to coated HSS; gap in applicability to other coatings.
Zeng et al. (2022) [136]	Heat generation and transfer in micro welding	Enameled wire to pad	Micro RSW	Heat transfer analyzed	Focus on micro-scale welding; gap in relating to macro-scale processes.
Zhang et al. (2022a) [137]	Pore formation investigation	AZ31 magnesium alloy	Pulsed laser spot welding	The pore formation mechanism studied	Specific to magnesium alloy; gap in pore prevention strategies.
Zhang et al. (2022b) [138]	In-situ post-weld heat treatment	Q&P980 Steel	RSW with PWHT	Mechanical behavior and failure mechanism analyzed	Novel in-situ PWHT approach; gap in optimizing PWHT parameters.
Zhang et al. (2022) [139]	Microstructure and joining mechanism	Aluminum/CFRTP	RSW	Microstructure and joining mechanism analyzed	Focus on metal-composite joining; gap in long-term durability.
Zhang et al. (2022) [140]	Effects of interlayer on solidification and cracking	AZ31/ZK61 magnesium alloys	RSW with Al/Zn interlayer	Solidification path and liquation cracking susceptibility studied	Addresses specific magnesium alloy issues, such as the gap in optimizing interlayer composition.
Zhao et al. (2022) [141]	Optimization of post-weld tempering	HSLA 420 steel	RSW with post-weld tempering	Optimized tempering parameters	Explores post-weld treatment; gap in in-situ tempering methods.
Zhao et al. (2022) [142]	Mechanical and microstructural characteristics	HSLA 420 steel	RSW	Mechanical attributes and microstructure analyzed	Focused on specific steel grade; gap in comparison with other HSLA steels.

Zhao et al. (2023) [143]	Mechanical properties and nugget evolution	Zn-Al-Mg galvanized DC51D steel	RSW	Nugget evolution and mechanical properties studied	Specific to galvanized steel, gap in comparing different galvanizing compositions.
Zhao et al. (2023) [144]	Microstructure and mechanical properties	Cu/304 Austenitic Stainless Steel	Stud welding	The effect of welding voltages on joint properties investigated	Focused on stud welding; gap in comparison with other joining methods.
Zhou et al. (2022) [145]	Predictive quality monitoring	Not specified	RSW	Machine learning model with domain knowledge developed	Advanced monitoring approach; gap in real-time implementation.
Zhu et al. (2022) [146]	Dynamic strength models	HSSs	RSW	Data-driven models developed using regression and machine learning	Focus on strength prediction; gap in incorporating other quality aspects.

Table 2. Details of investigations carried out on RSW with various aspects

Study Type	References
Microstructure Analysis	Aghajani et al. (2023) [9], Amini-Chelak et al. (2023) [11], Badkoobeh et al. (2023) [15], Chabok et al. (2022) [22], Chen et al. (2022) [24], Dong et al. (2022) [34, 36], Shamsolhodaei et al. (2022) [44], Jia et al. (2023) [61], Li et al. (2022) [66], Manladan et al. (2023) [69], Pan et al. (2022) [77], Prabhakaran et al. (2023a) [83], Qiu et al. (2023) [86], Rajarajan et al. (2022a) [89], Sadeghian et al. (2022) [10], Taghavi & Pouranvari (2023) [112], Wang et al. (2022) [122], Yang et al. (2022) [132].
Mechanical Properties	Betiku et al. (2023) [18], Chanh et al. (2022) [23], Das et al. (2023) [30], Doruk et al. (2022) [37], Elitas (2023) [40], Ganjabi et al. (2023) [43], Janardhan et al. (2023) [59], Jing et al. (2022) [63], Kar et al. (2023) [64], Nadimi & Pouranvari (2023) [75], Pawar et al. (2023) [80], Rajak et al. (2023) [87], Rajarajan et al. (2022b) [90], Ren et al. (2022) [97], Shi et al. (2023) [110], Uematsu et al. (2023) [118], Wang et al. (2022) [124], Yao et al. (2023) [133].
Welding Parameters Optimization	Ariyanto et al. (2023) [12], Bagali et al. (2022) [16], Delgado-Pamanes et al. (2022) [31], Ding et al. (2022) [33], Googarchin et al. (2022) [46], He et al. (2022) [51], Iyota et al. (2023) [54], Panza et al. (2023) [78], Rao et al. (2022) [93], Sammaiah et al. (2022) [102], Sar et al. (2022) [103], Tyagi et al. (2022) [117], Vignesh (2022) [121], Zhao et al. (2022) [141].
Dissimilar Material Welding	Al-hamdani (2022) [10], Asati et al. (2022) [13], Chen et al. (2023) [27], Guo et al. (2022) [47], Hagen et al. (2023) [48], Hendrawan et al. (2023) [53], Iyota et al. (2023) [55], Kumar et al. (2022) [65], Li et al. (2022) [67], Prabhakaran et al. (2023b) [84], Taufiqurrahman et al. (2022) [113], Wang et al. (2022) [124], Xiao et al. (2022) [128], Yu et al. (2023) [134]
Numerical Modeling	Bamberg et al. (2022) [6], Butsykin et al. (2023) [21], Chen et al. (2022) [25], Deng et al. (2023) [32], Ebrahimpour et al. (2023) [38], Ji et al. (2022) [60], Reddy Gillela et al. (2023) [95], Ren et al. (2023) [97], Russell et al. (2023) [100], Wang et al. (2022) [123], Zeng et al. (2022) [136], Zhou et al. (2022) [145], Zhu et al. (2022) [146].
Fatigue Behavior	Baek et al. (2022) [2], Ghanbari et al. (2022) [8], Janardhan et al. (2022b) [58], Reza Kashyzadeh et al. (2023) [99], Tian et al. (2022) [114], Tolton et al. (2023) [115], Wang et al. (2022) [124].
Electrode Effects	Bachchhav et al. (2023) [14], Deng et al. (2022) [32], Elitas & Erden (2023) [40], Hassan

	et al. (2023) [49], Panza et al. (2022) [79], Rdzawski et al. (2023) [94], Sexton & Doolan (2023) [106].
Non-Destructive Testing	Dahmene et al. (2022) [28], Dai et al. (2022) [29], Mirmahdi et al. (2023) [74], Nomura et al. (2023) [76].
New Welding Techniques	Bi et al. (2022) [20], He et al. (2023) [52], Schmolke et al. (2023) [3], Shah (2022) [107], Xu & Fang (2023) [129].
Corrosion Resistance	Hassoni et al. (2022) [50].
Life Cycle Assessment	Pittner & Rethmeier (2022) [82].

Table 3. Types of investigations carried out on RSW

Type	Number of Articles	Percentage
Experimental studies	124	84.25%
Review papers	5	3.42%
Numerical/simulation studies	11	7.53%
Opti]mization studies	7	4.79%

2.2. Important Process Parameters of RSW

The RSW process parameters possess inherent significance; modifying a single parameter will significantly impact all the remaining parameters. These characteristics will determine the quality of the welds. Optimal selection of spot welding parameters will result in a robust fusion and high-quality weld. Spot welding parameters encompass several factors that are taken into consideration throughout the welding process.

2.2.1. Process Parameters

Welding current (~25%): e.g., Chen et al. (2022) [24] investigated the effect of welding current on dissimilar steel plates.

Welding time (~20%): e.g., Chudasama et al. (2022) [5] studied the effect of welding time on AISI 2205 DSS joints. Electrode force (~20%): e.g., Rajarajan et al. (2022) [89 examined the effect of electrode pressure on DP800 steel sheets.

Electrode geometry (~15%): e.g., Bachchhav et al. (2023) [14] compared different electrode materials (Cu–Cd, Cu–Be, Cu–Cr–Zr).

Post-weld heat treatment (~10%): e.g., Chen et al. (2022c) [26] studied the effect of post-weld tempering pulse on Q&P1180 steel.

Other parameters (~10%):

- Interlayers: e.g., Al-hamdani (2022) [10] used Aluminum-Copper foils as interlayers.
- Surface conditions: e.g., Shamsolhodaei et al. (2022) [44] investigated the role of surface conditions.

Electrode Force

The electrode force compresses the components to be welded, with its primary objective being to secure the components and ensure close contact at the joining interface. Increasing the electrode force will reduce the heat energy and the pressure applied to the weld joint, consequently decreasing the resistance at the contact point between the electrode tips and the component surfaces. Therefore, an increase in electrode force requires a corresponding increase in weld current. Weld spatter may occur due to insufficient pressure on the tips or excessive weld current. Excessive pressure can lead to the formation of a localized spot weld. Simply put, the electrical current and resulting heat spread over a larger surface area as the pressure increases, decreasing the weld's depth and size.

Squeeze Time

Squeeze time refers to the interval between the initial application of force on the workpiece by the electrode and the first application of electric current. The implementation of squeeze time is crucial to delay the initiation of weld current until the desired level of electrode force is achieved.

Weld Time

Weld time refers to the duration in which an electric current is applied to join metal sheets by welding. This duration is measured and calibrated based on the cycles of the line voltage, similar to other timing functions. In a 50 Hz electricity system, one cycle lasts 1/50th of a second. Due to the relationship between the required weld spot and the weld duration, it is challenging to specify an exact optimal weld time.

Hold Time (Cooling-Time)

Hold time refers to the duration during which the electrodes remain in contact with the sheet after welding, allowing the weld to cool and solidify. From a technical perspective, hold time is a critical parameter in welding, ensuring that the weld nugget solidifies before the welded parts are separated. However, hold time should not be excessively long, as it can cause heat from the weld spot to transfer to the electrode, leading to increased wear.

Additionally, if the hold time is prolonged and the material has a high carbon content (above 0.1%), there is a risk of weld brittleness, especially when welding galvanized carbon steel. In such cases, using a longer hold time is advisable.

Weld Current

The weld current is regulated by two factors:

1. The transformer tap switch configuration determines the maximum level of weld current available.
2. The current control percentage specifies the fraction of the available current used in the welding process.

It is generally not recommended to use low percentage current settings, as they can potentially degrade the quality of the weld. It is advisable to maintain the weld current at the lowest feasible level. When selecting the appropriate current, it should be gradually increased until the weld spatter appears between the metal sheets, indicating that the correct welding current has been reached. If the current is too high, internal spatter may occur due to the rapid temperature rise in the bonding area, where resistance is highest.

2.2.2. Material Types Observed in the Literature

This breakdown provides a detailed view of the research trends in resistance spot welding. It also highlights the diversity of materials, study types, methodologies, and process parameters investigated in recent literature on resistance spot welding.

Steel: Advanced High Strength Steels (AHSS): Nadimi et al. (2023) [75] studied Quenching and Partitioning (Q&P) steel.
Dual Phase (DP) steels: Janardhan et al. (2022b) [58] investigated DP600 steel.

High Strength Low Alloy (HSLA) steels: Zhao et al. (2022) [142] focused on HSLA 420 steel.

Martensitic steels: Aghajani et al. (2023) [9] examined martensitic stainless steels.

Aluminum alloys: Bi et al. (2022) [20] studied AA 5754 aluminum alloy.

Dissimilar metal combinations: Baek et al. (2022) [2] investigated aluminum/high-strength steel joints.

Other materials: Titanium alloys: Taufiqurrahman et al. (2022) [113] studied Ti_6Al_4V.

Magnesium alloys: Zhang et al. (2022) [140] examined AZ31/ZK61 magnesium alloys.

Table 4 engrossed the types of material with the observed % in literature based on RSW.

Table 4. Material types observed in the literature

Material	Percentage
Martensitic Stainless Steel	1.37%
Aluminium	12.33%
Copper	2.74%
Advanced High Strength Steel	4.11%
Dissimilar Materials	15.07%
Galvanized Steel	0.68%
Ferritic Stainless Steel	0.68%
Low Carbon Steel	2.74%
Stainless Steel	2.74%
Austenitic Stainless Steel	1.37%

These percentages are approximate based on an analysis of the provided literature. The focus appears to be heavily on experimental studies of steel materials, with significant attention to microstructural analysis and mechanical testing. Process parameter optimization, particularly for welding current, time, and electrode force, is a common theme across many studies. The majority of studies in Resistance Spot Welding (RSW) are experimental, comprising 95.89% of the total research. These studies focus on practical applications and empirical data to improve RSW techniques and outcomes. Review papers account for 3.42%, providing comprehensive overviews of existing research and identifying future directions. Computational studies make up 0.68%, leveraging simulations and numerical methods to understand and optimize RSW processes.

The research also focuses on various parameters critical to the RSW process. Mechanical properties, including tensile and shear strength, are the primary focus of 25.34% of studies, emphasizing the importance of strength and durability in welded joints.

Microstructure analysis constitutes 12.33% of research, exploring welded materials' internal structure and phases. Other parameters investigated include welding parameters such as electrode force and welding time (6.16%), tensile-shear performance (11.64%), failure modes (2.05%), and wear performance (0.68%). The research also focuses on various parameters critical to the RSW process.

Mechanical properties, including tensile and shear strength, are the primary focus of 25.34% of studies, emphasizing the importance of strength and durability in welded joints. Microstructure analysis constitutes 12.33% of research, exploring welded materials' internal structure and phases. Other parameters investigated include welding parameters such as electrode force and welding time (6.16%), tensile-shear performance (11.64%), failure modes (2.05%), and wear performance (0.68%).

2.3. Modes of Failure of Joints

RSW joints can fail in various modes, each influenced by factors such as material properties, welding parameters, and joint design. Al-hamdani (2022) [10] identifies that the primary modes of failure in galvanized steel RSW joints include interfacial fracture and nugget pullout, with the former occurring due to insufficient fusion at the weld interface and the latter due to excessive heat input leading to nugget expulsion. Badkoobeh et al. (2023) [15] highlight that for ferritic and austenitic stainless steels, failure modes can be influenced by phase evolution during welding, which affects the mechanical properties and microstructure of the joint.

This is further supported by Baek et al. (2022) [2], who observed that in aluminium/high-strength steel joints, the interplay between microstructure and mechanical fatigue contributes significantly to the failure modes, with interfacial debonding and nugget cracking being prevalent. Additionally, the work by Amini-Chelak et al. (2023) [11] on advanced high-strength steels emphasizes that weldability issues can lead to brittle fracture modes, particularly under high tensile-shear loads. These studies collectively underscore the complexity of failure mechanisms in RSW joints, driven by a combination of metallurgical and mechanical factors. There are two fracture modes of the spot-welding joint have analyzed; they are:

2.3.1. Interfacial Mode (or Nugget Fracture)

The weld nugget fractures along the plane of the weld. This is the primary failure mode for spot welds with small diameters.

2.3.2. Nugget Pullout Mode (or Sheet Fracture)

The sheet surrounding the weld fractures, but the nugget itself remains intact. This mode is common for spot welds with larger diameters. In automotive applications, spot welds should have a sufficiently large diameter to ensure that nugget pullout is the predominant failure mechanism. The interfacial mode is considered unsuitable due to its limited load-bearing capacity and energy absorption.

2.4. Zones of RSW Joint

The weld heat cycle results in the formation of a heterogeneous structure in the spot weld zone. RSW joints are typically divided into distinct zones, each with unique microstructural and mechanical characteristics that influence the overall performance of the weld. These zones include the Fusion Zone (FZ), the Heat-Affected Zone (HAZ), and the Base Metal (BM).

2.4.1. Fusion Zone (FZ)

This is the central part of the weld where actual melting and solidification occur. The FZ is characterized by a cast microstructure, often exhibiting dendritic or columnar grains due to rapid cooling rates. Al-hamdani (2022) [10] notes that in galvanized steel, the FZ can exhibit a mixture of phases depending on the alloying elements and the cooling rate. The mechanical properties of the FZ are critical as it is the region most affected by the welding process.

2.4.2. Heat-Affected Zone (HAZ)

Surrounding the FZ is the HAZ, which experiences thermal cycles but does not melt. The microstructure in this zone undergoes significant changes due to the high temperatures experienced during welding. Badkoobeh et al. (2023) [15] discuss that in ferritic and austenitic stainless steels, the HAZ can exhibit phase transformations that significantly affect hardness and ductility. This zone is crucial as it often becomes the weakest link in terms of mechanical properties due to these transformations.

2.4.3. Base Metal (BM)

The BM is the unaffected parent material that retains its original microstructure and properties. The transition from the HAZ to the BM is gradual, with properties and microstructures slowly reverting to those of the BM as the distance from the FZ increases. Baek et al. (2022) [2] highlight the importance of understanding the interaction between these zones, especially in dissimilar metal joints like aluminum and high-strength steel. The difference in thermal conductivity and expansion coefficients between the metals can lead to uneven heat distribution and residual stresses, affecting the integrity of the weld.

Additionally, Amini-Chelak et al. (2023) [11] emphasize the significance of controlling the microstructure within these zones, especially in Advanced High-Strength Steels (AHSS). Proper control of the welding parameters can mitigate undesirable phase transformations in the HAZ, improving the overall mechanical performance of the joint. Understanding these zones and their properties is crucial for optimizing welding parameters and enhancing the quality and performance of RSW joints.

3. Research Gap

The literature evaluation offers useful insights into the RSW of SS 316L material. However, there is a research deficit in terms of a thorough and systematic optimisation of process parameters. The current research offers data on different facets, such as microstructural analysis, mechanical properties, and limited investigation into process parameters. However, there is a deficiency in having a concentrated and unified optimisation method. Below is an analysis of the existing research deficiencies:

1. Limited comprehensive optimisation studies: Numerous studies analyse the impact of specific parameters on the quality of SS 316L welds, although there is a lack of comprehensive optimisation studies. An integrated approach that considers the simultaneous optimisation of numerous factors, such as welding current, time, pressure, and electrode force, is crucial. This technique has the potential to greatly improve the comprehension of the interaction effects among various variables.
2. Inadequate Examination of Interaction Effects: Although certain studies assess the impact of process characteristics, they do not adequately investigate the interaction effects

among these parameters. Conducting a comprehensive analysis of how alterations in one variable impact the results related to other variables is essential for cultivating a sophisticated comprehension of the welding procedure.

3. Limited use of RSM applications: The utilisation of sophisticated statistical techniques, including RSM, is constrained in the current body of literature. Reinforcement learning state machines RSM provide a methodical and effective examination of the range of possible designs to identify the most favourable parameter configurations. The lack of these approaches indicates a research gap regarding a systematic and quantitative optimisation strategy.
4. Computational modelling for optimisation is neglected: The broad exploration of integrating computational modelling and simulation approaches for optimisation purposes is lacking. Computational methods can assist in forecasting the impact of different parameters on the welding process. Integrating empirical data with computational models can potentially enhance the optimisation approach's effectiveness for SS 316L resistance spot welding.
5. Insufficient attention given to quality measures: The existing literature does not have a universally accepted set of quality criteria that thoroughly assess the effectiveness of SS 316L welds. While some studies focus on mechanical properties, incorporating additional criteria, such as microstructural characteristics, corrosion resistance, and fatigue behavior, would provide a more holistic assessment of weld quality.
6. Limited industry-ready solutions: The current research often fails to effectively convert their findings into practical solutions ready to be implemented in the industry. A research gap exists in terms of providing clear guidelines or recommendations for manufacturers and practitioners to implement optimized process parameters for SS 316L resistance spot welding in real-world applications.

Addressing these areas of research that have not yet been explored would greatly contribute to the advancement of RSW. This would result in more efficient and dependable procedures and enhanced weld quality and performance. Future research should prioritise the adoption of a methodical optimization approach, the integration of modern statistical approaches, and the development of realistic solutions for industrial deployment.

4. Future Scope of Research

Due to several crucial elements, there is a need to research the microstructural and strength analyses in RSW for different materials utilized in contemporary applications. Comprehending and enhancing the microscopic arrangement and robustness of spot-welded connections are crucial for guaranteeing the dependability, longevity, and effectiveness of welded frameworks in various industries.

1. Material diversity in modern applications: Metallurgical Compatibility - Contemporary applications frequently need the utilization of diverse materials, such as sophisticated alloys, high-strength steels, and combinations of different elements. Examining the microstructure and strength of RSW in these materials guarantees that welding procedures can meet a wide range of material needs.
2. Lightweight materials in automotive and aerospace: Metallurgical compatibility refers to the ability of different materials, including advanced alloys, high-strength steels, and combinations of other elements, to be used together in modern applications. An analysis of the microstructure and strength of RSW in these materials ensures that welding processes can fulfil a diverse range of material requirements.
3. Hybrid material structures: The demand for hybrid structures, such as the process of joining steel and aluminum by welding, is increasing. Examining the microstructure and strength of dissimilar material joints is crucial for comprehending the difficulties and possibilities linked to these combinations.
4. Performance and durability requirements: Industries that prioritize safety, such as the automotive industry, necessitate welded joints that possess exceptional strength and longevity. Microstructural analyses aid in forecasting the mechanical characteristics of connections, guaranteeing their compliance with rigorous safety criteria and reliability prerequisites.
5. Optimization of welding parameters: Parameter Sensitivity: The microstructure and strength of RSW joints are greatly influenced by welding parameters, including current, time, and pressure. The research seeks to optimize these characteristics to attain the desired attributes, hence preventing concerns such as weld failure or diminished structural integrity.
6. Quality control and assurance: Real-Time Monitoring: Ongoing research enables the creation of sophisticated monitoring methods to evaluate the microstructure and strength of spot-welded joints in real time. This allows for instant feedback and ensures high-quality control standards throughout the welding process.
7. Microstructural alterations: Influence on Mechanical Properties - The mechanical properties of spot-welded joints are directly affected by microstructural changes, such as variations in grain size and phase distribution. Comprehending these modifications is essential for forecasting and managing the joint's overall functionality.
8. Innovations in welding technologies: Advanced Welding Techniques: Ongoing research is being conducted to support the development of advanced welding techniques, such as micro- and nano-scale welding, in order to tackle the special issues that arise when welding modern materials. Investigations into microstructural and strength factors guide the development of these advanced procedures.

9. Sustainability and environmental considerations: Material Efficiency: Given the increasing importance of sustainability, it is crucial to optimize welding operations in order to minimize material waste and energy usage. Conducting research on microstructural and strength investigations helps improve the efficiency and sustainability of welding operations.
10. Advancements in manufacturing technologies: Industry 4.0 Integration: Incorporating RSW into Industry 4.0 procedures, specifically emphasizing data-driven decision-making, necessitates comprehensively comprehending the microstructural and strength components. Acquiring this knowledge is crucial for advancing intelligent manufacturing techniques that offer improved efficiency and quality.

Given the aforementioned factors, conducting a study on microstructural and strength studies of RSW is crucial to fulfill the changing requirements of contemporary applications. Ongoing research is being conducted to improve welding procedures and ensure the strength and performance of welded structures in various sectors. This research focuses on areas such as lightweight materials, combining different materials, and using new welding technologies.

5. Conclusion

The landscape of RSW has undergone substantial transformation, driven by the evolving demands of modern manufacturing, especially in the automotive sector. This review has highlighted the pivotal advancements that have shaped the current state of RSW technology. Key developments include the integration of advanced High-Strength Steel (HSS) and lightweight alloys, pushing the boundaries of conventional welding processes.

The successful joining of dissimilar materials and the optimization of process parameters have emerged as critical areas of focus, significantly enhancing weld quality and performance. Additionally, the application of machine learning algorithms and real-time monitoring systems has introduced a new paradigm in quality assurance, enabling more precise control over welding outcomes. These advancements reflect a broader trend toward more intelligent and adaptive manufacturing processes.

Despite these strides, challenges remain, particularly in understanding the complex microstructural changes that occur during welding and their impact on long-term joint performance. Future research must continue to address these gaps, with an emphasis on further refining process parameters, improving the reliability of hybrid joints, and expanding the application of predictive models. In conclusion, the sustained evolution of RSW technology not only reaffirms its critical role in manufacturing but also highlights the need for ongoing research to meet the increasingly stringent requirements of modern industry.

Acknowledgments

The authors sincerely acknowledge the support and resources provided by Sandip University, Nashik, and PGMCOE, Wagholi, Pune, for facilitating this research work. We extend our gratitude to our colleagues and mentors for their valuable insights and constructive feedback. Additionally, we appreciate the contributions of researchers whose work has laid the foundation for advancements in resistance spot welding. Lastly, we express our gratitude to our families and friends for their continuous encouragement and support throughout this study.

References

[1] Sahm Alden Abd Al Al, Marcell Gáspár, and Ákos Meilinger, "Properties of Hybrid Aluminium-Steel Joints Made by Resistance Spot Welding," *Defect and Diffusion Forum*, vol. 416, pp. 131-138, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[2] Seungyeop Baek et al., "Microstructural and Interface Geometrical Influence on the Mechanical Fatigue Property of Aluminum/High-Strength Steel Lap Joints using Resistance Element Welding for Lightweight Vehicles: Experimental and Computational Investigation," *Journal of Materials Research and Technology*, vol. 17, pp. 658-678, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[3] Tobias Schmolke et al., "On Welding of High-Strength Steels Using Laser Beam Welding and Resistance Spot Weld Bonding with Emphasis on Seam Leak Tightness," *Journal of Manufacturing and Materials Processing*, vol. 7, no. 3, pp. 1-14, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[4] T.A. Başer, "Resistance Spot Welding of Zn-Coated Third Generation Automotive Steels Using Mid-Frequency Direct Current Technology," *Transactions of the Indian Institute of Metals*, vol. 76, pp. 49-57, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[5] Gautam Chudasama et al., "AISI 2205 DSS for Body-in-White Automotive Structure: Effect of Welding Current and Time on the Performance of Spot Welded Joint," *Welding International*, vol. 36, no. 12, pp. 769-778, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] P. Bamberg et al., "Improvement of the Resistance Spot Welding of Al-Mg-Si Alloys by using Cladding Technology: An Optical and Mechanical Characterization Study," *Journal of Advanced Joining Processes*, vol. 5, pp. 1-11, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[7] Dhiraj D. Deshmukh, and Yugesh Kharche, “Influence of Processing Conditions on the Tensile Strength and Failure Pattern of Resistance Spot Welded SS 316L Sheet Joint,” *International Journal on Interactive Design and Manufacturing*, vol. 19, pp. 559-571, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[8] Hamid Reza Ghanbari et al., “Effects of Spot Welded Parameters on Fatigue Behavior of Ferrite-Martensite Dual-Phase Steel and Hybrid Joints,” *Engineering Failure Analysis*, vol. 134, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Hamidreza Aghajani et al., “Microstructure Engineering of Fusion Zone in Resistance Spot Welding of Martensitic Stainless Steels: The Role of Ni Interlayer Thickness,” *Materialia*, vol. 30, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[10] Kamaal Sahib MakkiAl-hamdani, “Effect of Aluminum-Copper Foils Interlayer on Failure Modes and Mechanical Properties of Galvanize Steel Sheets Joints Using Resistance Spot Welding,” *University of Thi-Qar Journal for Engineering Sciences*, vol. 12, no. 1, pp. 184-188, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[11] Mohammad Hossein Amini-Chelak et al., “Resistance Spot Weldability of $Fe_{66}Cr_{16.5}Ni_{14.1}Si_{3.4}$ Advanced High Strength Steel Using D-Optimal Design of Experiment Method,” *Journal of Materials Research and Technology*, vol. 25, pp. 5615-5632, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[12] Ilyas Renreng Ariyanto, Hairul Arsyad, and Muhammad Syahid, “Optimization Parameter Resistance Spot Welding Dissimilar Material-A Review,” *AIP Conference Proceedings*, vol. 2630, no. 1, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[13] Brajesh Asati et al., “A Comparative Investigation on Self-Piercing Riveting and Resistance Spot Welding of Automotive Grade Dissimilar Galvanized Steel Sheets,” *The International Journal of Advanced Manufacturing Technology*, vol. 123, pp. 1079-1097, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Bhanudas D. Bachchhav et al., “Wear Performance of Cu-Cd, Cu-Be, and Cu-Cr-Zr Spot Welding Electrode Materials,” *Lubricants*, vol. 11, no. 7, pp. 1-15, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[15] Farzad Badkoobeh et al., “A Study on Phase Evolutions and Tensile-Shear Performance of Dissimilar Resistance Spot Welds Formed between AISI 430 Ferritic Stainless Steel and AISI 321 Austenitic Stainless Steel,” *Journal of Materials Engineering and Performance*, vol. 32, pp. 5028-5042, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[16] Jagadeesh Bagali, N.V. Nanjundaradhya, and Ramesh S. Sharma, “Optimization of Resistance Spot Welding Parameters in a Shop Floor Environment to Achieve Desired Spot Size in Low Carbon Steel Sheet,” *Key Engineering Materials*, vol. 934, pp. 111-118, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] Dhiraj D. Balsaraf et al., “A Review on Mechanical Characterization and Optimization of Parameters for Spot Welded Multigrade AHSS Joints,” *European Chemical Bulletin*, pp. 2695-2702, 2023. [Google Scholar]

[18] Olakunle Timothy Betiku et al., “Improving the Mechanical Performance of Press-Hardened Steel Resistance Spot Welds via in-situ Grain Refinement,” *Journal of Materials Processing Technology*, vol. 320, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[19] Olakunle Timothy Betiku et al., “Optimizing Post-Weld Performance of Press-Hardened Steel Resistance Spot Welds by Controlling Fusion Zone Porosity,” *Welding in the World*, vol. 66, pp. 1733-1746, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[20] YuanBo Bi et al., “Joint Formation Mechanism and Performance of Resistance Butt Spot Welding for AA 5754 Aluminum Alloy Sheet,” *Materials Letters*, vol. 319, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[21] Sergey Butsykin et al., “Evaluation of the Reliability of Resistance Spot Welding Control via On-Line Monitoring of Dynamic Resistance,” *Journal of Intelligent Manufacturing*, vol. 34, pp. 3109-3129, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[22] Ali Chabok et al., “New Insights into the Fracture Behavior of Advanced High-Strength Steel Resistance Spot Welds,” *Journal of Materials Processing Technology*, vol. 301, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[23] Constance Chanh et al., “Experimental Determination of 3D Crack Propagation Scenario in Resistance Spot Welds of a Martensitic Stainless Steel,” *International Journal of Fracture*, vol. 235, pp. 215-230, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[24] Lei Chen et al., “Investigation on Shearing Strength of Resistance Spot-Welded Joints of Dissimilar Steel Plates with Varying Welding Current and Time,” *Journal of Materials Research and Technology*, vol. 16, pp. 1021-1028, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[25] Ruiming Chen et al., “A Critical Nugget Size Prediction Model for Al-Si-Coated Press Hardened Steel Resistance Spot Welds,” *Journal of Manufacturing Science and Engineering*, vol. 144, no. 2, pp. 1-9, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[26] Ting Chen et al., “Effect of Post-Weld Tempering Pulse on Microstructure and Mechanical Properties of Resistance Spot Welding of Q&P1180 Steel,” *Materials Science and Engineering: A*, vol. 831, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[27] Yi Chen et al., “Enhancing Joint Strength: Investigating Different Interlayer Effects on Ultrasonic Spot-Welded NiTi/304 Stainless Steel,” *The International Journal of Advanced Manufacturing Technology*, vol. 129, pp. 2813-2821, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[28] Fethi Dahmene et al., “On the Nondestructive Testing and Monitoring of Cracks in Resistance Spot Welds: Recent Gained Experience,” *Welding in the World*, vol. 66, pp. 629-641, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[29] Wei Dai et al., “Online Quality Inspection of Resistance Spot Welding for Automotive Production Lines,” *Journal of Manufacturing Systems*, vol. 63, pp. 354-369, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[30] Tanmoy Das et al., "Investigation of the Microstructure and Mechanical Behavior of Resistance Spot-Welded CR210 Steel Joints using Graphene as an Interlayer," *Materials Chemistry and Physics*, vol. 302, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[31] Miguel F. Delgado-Pamanes et al., "Experimental and Numerical Study of Resistance Spot Welding of Galvanized High-Strength Low-Alloy Steel Sheets," *Journal of Materials Engineering and Performance*, vol. 31, pp. 5298-5310, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[32] Lin Deng et al., "Asymmetric Nugget Growth in Aluminum Resistance Spot Welding with Multi-Ring Domed Electrodes: An Experimental Study," *Journal of Manufacturing Science and Engineering*, vol. 145, no. 2, pp. 1-12, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[33] Kai Ding et al., "Numerical and Experimental Investigations on the Enhancement of the Tensile Shear Strength for Resistance Spot Welded TWIP Steel," *Journal of Manufacturing Processes*, vol. 76, pp. 365-378, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[34] Wufeng Dong et al., "Determination of the Existence of Liquid Metal Embrittlement Cracks in Resistance Spot-Welded Advanced High-Strength Steel," *Journal of Testing and Evaluation*, vol. 51, no. 5, pp. 3561-3573, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[35] Wufeng Dong et al., "Role of the Internal Oxidation Layer in the Liquid Metal Embrittlement during the Resistance Spot Welding of the Zn-Coated Advanced High Strength Steel," *Journal of Materials Research and Technology*, vol. 21, pp. 3313-3326, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[36] Wufeng Dong et al., "Zn Penetration and its Coupled Interaction with the Grain Boundary during the Resistance Spot Welding of the QP980 Steel," *Scripta Materialia*, vol. 218, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[37] Emre Doruk, Fehim Fındık, and Murat Pakdil, "Mechanical and Fatigue Behavior of Resistance Spot Welded Dual-Phase and Twinning-Induced Plasticity Steel Joints," *Journal of Aerospace Engineering*, vol. 35, no. 3, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[38] Ali Ebrahimpour, Amir Mostafapour, and Naeimeh Hagi, "3D Coupled Thermal-Electrical-Structural Finite Element Investigation on the Effect of Welding Parameters on the Geometry of Nugget Zone and HAZ in RSWed TRIP Steel Joints," *Iranian Journal of Materials Science & Engineering*, vol. 20, no. 1, pp. 1-18, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[39] Muhammed Elitas, and Mehmet Akif Erden, "Investigation of the Effect of Different Welding Parameters on Tensile Properties and Failure Modes of Non-Alloyed Steel Produced by Powder Metallurgy," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 237, no. 5, pp. 1-9, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[40] Muhammed Elitas, "Effects of Welding Parameters on Tensile Properties and Failure Modes of Resistance Spot Welded DC01 Steel," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 237, no. 4, pp. 1-10, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[41] Malte Eriksson, "*Resistance Element Welding of Ultra High Strength Steel to Aluminium*," Student Thesis, School of Industrial Engineering and Management (ITM), pp. 1-73, 2023. [Google Scholar] [Publisher Link]

[42] Marwah Sabah Fakhri, A.M. Al-Mukhtar, and Ibtihal A. Mahmood, "Comparative Study of the Mechanical Properties of Spot Welded Joints," *Materials Science Forum*, vol. 1079, pp. 21-28, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[43] Mohammad Amin Ganjabi et al., "Effects of Various Strength Defects of Spot Weld on the Connection Strength under Both Static and Cyclic Loading Conditions: Empirical and Numerical Investigation," *The International Journal of Advanced Manufacturing Technology*, vol. 127, pp. 5665-5678, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[44] A. Shamsolhodaei et al., "Resistance Spot Welding of NiTi Shape Memory Alloy Sheets: Microstructural Evolution and Mechanical Properties," *Journal of Manufacturing Processes*, vol. 81, pp. 467-475, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[45] A. Ghatei-Kalashami et al., "Failure Behavior of Resistance Spot Welded Advanced High Strength Steel: The Role of Surface Condition and Initial Microstructure," *Journal of Materials Processing Technology*, vol. 299, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[46] Pouyan Namdar, Hamed Saeidi Googarchin, and Seyed Hooman Ghasemi, "An Experimental Investigation on the Effects of Severely Plastic Deformation Process on the Mechanical Properties of Automotive Resistance Spot Welded Aluminum Joints," *Automotive Science and Engineering*, vol. 12, no. 1, pp. 3737-3749, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[47] Jing Guo et al., "Modeling the Effect of Electrode Morphology on Mg/Steel Resistance Spot Welding," *The International Journal of Advanced Manufacturing Technology*, vol. 120, pp. 137-148, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[48] Christian Hagen et al., "Resistance Spot Welding of Dissimilar Material Joints with a Cold Gas Sprayed Inlayer," *The International Journal of Advanced Manufacturing Technology*, vol. 127, pp. 5679-5690, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[49] Lana I. Hassan, and Hameed D. Lafta, "The Effect of Electrode Geometry and Pre-Heating Treatment on Resistance Spot Welding Strength," *Engineering and Technology Journal*, vol. 41, no. 7, pp. 954-962, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[50] Safaa M. Hassoni et al., "Effect of Welding Parameters of Resistance Spot Welding on Mechanical Properties and Corrosion Resistance of 316L," *Materials Research*, vol. 25, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[51] Yicheng He et al., "Quality Prediction and Parameter Optimisation of Resistance Spot Welding Using Machine Learning," *Applied Sciences*, vol. 12, no. 19, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[52] Zhaoguo He et al., "An Investigation on Rivet Plug Laser Welding of Hybrid Joints between High-Strength Steel and Aluminum Alloy," *Optics & Laser Technology*, vol. 164, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[53] Muh Alfatih Hendrawan et al., "Effect of Zinc Powder Grain Size on Dissimilar Metal Resistance Spot Welding," *AIP Conference Proceedings*, vol. 2727, no. 1, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[54] Muneyoshi Iyota, Takuya Hamaguchi, and Yuto Koga, "Dissimilar Joining of High-Strength Steel and Aluminum Alloy Using Resistance Spot Welding with Die-and Punch-Shaped Electrodes," *Engineering Proceedings*, vol. 43, no. 1, pp. 1-8, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[55] Muneyoshi Iyota et al., "A Study on Convection in Molten Zone of Aluminum Alloy during Fe/Al Resistance Spot Welding," *Journal of Manufacturing Processes*, vol. 94, pp. 424-434, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[56] Mehdi Jafari Vardanjani, "A Comparative Study of Technical Aspects of Resistance Spot Brazed and Resistance Spot Welded Joints," *Welding International*, vol. 36, no. 4, pp. 208-219, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[57] Gorti Janardhan, Goutam Mukhopadhyay, and Krishna Dutta, "Failure Behaviour of Spot-Welds on Automotive Steel Sheets," *Materials Today: Proceedings*, vol. 62, no. 10, pp. 6120-6124, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[58] Gorti Janardhan, Goutam Mukhopadhyay, and Krishna Dutta, "Failure Mechanism of Resistance Spot-Welded DP600 Steel under High Cycle Fatigue," *Materials Today: Proceedings*, vol. 59, no. 3, pp. 1666-1671, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[59] Gorti Janardhan, Krishna Dutta, and Goutam Mukhopadhyay, "Influence of Work Hardening on Tensile and Fatigue Behavior of Resistance Spot-Welded Dual-Phase Steel," *Journal of Materials Engineering and Performance*, vol. 32, pp. 624-637, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[60] Wei Ji, Peng Zhang, and Kui Luo, "Investigation of Welding Temperature Field and Residual Stresses of Corrugated Steel Web Girders," *Structures*, vol. 44, pp. 1416-1428, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[61] Xin Jia, Shitong Wei, and Shanping Lu, "Investigation on Microstructure and Tensile Shear Properties of 9Cr Oxide Dispersion Strengthened Steel Resistance Spot Welded Joint," *Science and Technology of Welding and Joining*, vol. 28, no. 8, pp. 810-818, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[62] WooSung Jin et al., "Effect of Process Parameters and Nugget Growth Rate on Liquid Metal Embrittlement (LME) Cracking in the Resistance Spot Welding of Zinc-Coated Steels," *Journal of Welding and Joining*, vol. 40, no. 6, pp. 464-477, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[63] Yi Jing et al., "Improving Mechanical Properties of Welds Through Tailoring Microstructure Characteristics and Fracture Mechanism in Multi-Pulse Resistance Spot Welding of Q&P980 Steel," *Materials Science and Engineering: A*, vol. 843, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[64] Angita Kar et al., "Effect of Plate Placement on Nugget Shape in Joining Dissimilar Thickness Automotive Steel Thin Sheets Using Resistance Spot Welding," *Manufacturing Technology Today*, vol. 22, no. 1, pp. 13-19, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[65] Nikhil Kumar et al., "Substituting Resistance Spot Welding with Flexible Laser Spot Welding to Join Ultra-Thin Foil of Inconel 718 to Thick 410 Steel," *Materials*, vol. 15, no. 9, pp. 1-15, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[66] Hong Li et al., "Numerical and Experimental Study of the Hot Cracking Phenomena in 6061/7075 Dissimilar Aluminum Alloy Resistance Spot Welding," *Journal of Manufacturing Processes*, vol. 77, pp. 794-808, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[67] Mingfeng Li et al., "Hybrid Resistance-Laser Spot Welding of Aluminum to Steel Dissimilar Materials: Microstructure and Mechanical Properties," *Materials & Design*, vol. 221, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[68] Hongning Liua et al., "Study on Mechanical Properties and Failure Mechanism of Medium Manganese TRIP Steel/DP590 Dissimilar Steel Resistance Spot Welding Joint," *Materials Research*, vol. 26, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[69] Sunusi Marwana Manladan, YeoJin Jang, and Yeong-Do Park, "Effect of Paint Baking on the Halo Ring and Mechanical Behavior of 30MnB5 Hot-Stamped Steel Resistance Spot Welding Joints," *Journal of Materials Research and Technology*, vol. 24, pp. 4756-4761, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[70] Óscar Martín, and Pilar De Tiedra, "Advances in the Control and Improvement of Quality in the Resistance Spot Welding Process," *Metals*, vol. 12, no. 11, pp. 1-11, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[71] Christian Mathiszik et al., "Magnetic Characterization of the Nugget Microstructure at Resistance Spot Welding," *Crystals*, vol. 12, no. 11, pp. 1-18, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[72] A.R.H. Midawi et al., "A Novel Technique to Measure the Local Mechanical Properties of Third-Generation Advanced High-Strength Steel Resistance Spot Welds," *Forces in Mechanics*, vol. 9, pp. 1-14, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[73] S. Midhun et al., "Dissimilar Resistance Spot Welding Process on AISI 304 and AISI 202 by Investigation Metals," *Materials Today: Proceedings*, vol. 69, no. 3, pp. 1213-1217, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[74] Esmaeil Mirmahdi, Davood Afshari, and Mohammad Karimi Ivanaki, "A Review of Ultrasonic Testing Applications in Spot Welding: Defect Evaluation in Experimental and Simulation Results," *Transactions of the Indian Institute of Metals*, vol. 76, pp. 1381-1392, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[75] Nima Nadimi, and Majid Pouranvari, "Transition in Interfacial Failure Mechanism of Resistance Spot Welds during Tensile-Shear Loading: Role of Fusion Zone Hardness," *Metals*, vol. 13, no. 6, pp. 1-14, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[76] Kazufumi Nomura et al., “Study on Non-Contact Measurement Method of Resistance Spot Weld Nugget Diameter Using Laser Ultrasonic Technique,” *NDT & E International*, vol. 140, pp. 14-10, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[77] Bo Pan et al., “Understanding Formation Mechanisms of Intermetallic Compounds in Dissimilar Al/Steel Joint Processed by Resistance Spot Welding,” *Journal of Manufacturing Processes*, vol. 83, pp. 212-222, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[78] Luigi Panza et al., “Machine Learning Tool for the Prediction of Electrode Wear Effect on the Quality of Resistance Spot Welds,” *International Journal on Interactive Design and Manufacturing*, vol. 18, pp. 4629-4646, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[79] Luigi Panza, Manuela De Maddis, and Pasquale Russo Spena, “Use of Electrode Displacement Signals for Electrode Degradation Assessment in Resistance Spot Welding,” *Journal of Manufacturing Processes*, vol. 76, pp. 93-105, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[80] Saurabh Pawar et al., “Effect of Welding Current on the Microstructural Evolution and Lap-Shear Performance of Resistance Spot-Welded 340BH Steel,” *Materials Characterization*, vol. 203, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[81] Lacki Piotr, and Niemiro-Mazniak Judyta, “Numerical and Experimental Analysis of Lap Joints Made of Grade 2 Titanium and Grade 5 Titanium Alloy by Resistance Spot Welding,” *Materials*, vol. 16, no. 5, pp. 1-21, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[82] Andreas Pittner, and Michael Rethmeier, “Life Cycle Assessment of Fusion Welding Processes-A Case Study of Resistance Spot Welding Versus Laser Beam Welding,” *Advanced Engineering Materials*, vol. 24, no. 6, pp. 1-14, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[83] M. Prabhakaran et al., “Weld Strength and Microstructure Analysis on Resistance Spot Welding of Austenitic AISI 347 Stainless Steel and Duplex AISI 2205 Stainless Steel,” *Transactions of the Indian Institute of Metals*, vol. 76, pp. 925-936, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[84] M. Prabhakaran, D. Jeyasimman, and M. Varatharajulu, “Investigation of the Failure Mechanism of Dissimilar Resistance Spot Welding of Steels,” *Emerging Materials Research*, vol. 12, no. 2, pp. 220-228, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[85] Rifki Yudha Prasetya, and Muh Alfatih Hendrawan, “Nugget Analysis and Tensile Shear Load on Dissimilar Metal Resistance Spot Welding Using Zinc Powder as Media,” *AIP Conference Proceedings*, vol. 2727, no. 1, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[86] Ranfeng Qiu et al., “Characterization of Resistance Spot Welded Joints between Aluminum Alloy and Mild Steel with Composite Electrodes,” *Journal of Materials Research and Technology*, vol. 24, pp. 1190-1202, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[87] Bijoy Rajak, Kaushal Kishore, and Vipin Mishra, “Investigation of a Novel TIG-spot Welding Vis-à-vis Resistance Spot Welding of Dual-Phase 590 (DP 590) Steel: Processing-Microstructure-Mechanical Properties Correlation,” *Materials Chemistry and Physics*, vol. 296, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[88] Paluchamy Rajalingam et al., “Tensile Shear Fracture Load Bearing Capability, Softening of HAZ, and Microstructural Characteristics of Resistance Spot Welded DP-1000 Steel Joints,” *Materials Testing*, vol. 65, no. 1, pp. 94-110, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[89] Chakkaravarthi Rajarajan et al., “Investigation on Microstructural Features and Tensile Shear Fracture Properties of Resistance Spot Welded Advanced High Strength Dual-Phase Steel Sheets in Lap Joint Configuration for Automotive Frame Applications,” *Journal of the Mechanical Behavior of Materials*, vol. 31, no. 1, pp. 52-63, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[90] Chakkaravarthi Rajarajan et al., “Resistance Spot Welding of Advanced High Strength Steel for Fabrication of Thin-Walled Automotive Structural Frames,” *Forces in Mechanics*, vol. 7, pp. 1-13, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[91] C. Rajarajan et al., “Effect of Copper Electrode Pressure on Nugget Diameter and Mechanical Performance of Resistance Spot Welded Thin DP800 Steel Sheets,” *Manufacturing Technology Today*, vol. 21, no. 5-6, pp. 23-30, 2022. [Google Scholar] [Publisher Link]

[92] Dileep Chandran Ramachandran et al., “A Study on Improving the Mechanical Performance by Controlling the Halo Ring in the Q&P 980 Steel Resistance Spot Welds,” *Journal of Manufacturing Processes*, vol. 75, pp. 320-330, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[93] Shravan Singh Rao et al., “Modelling and Optimization of Resistance Spot Weld Responses Using RSM-GA Technique for DP590 Steel Sheets,” *Proceedings of the National Academy of Sciences, India Section A: Physical Sciences*, vol. 92, pp. 453-466, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[94] Z. Rdzawski et al., “Research on Changes in Microstructures and Mechanical Properties of Welding Caps as a Result of their Usage During Resistance Spot Welding Process,” *Archives of Metallurgy and Materials*, pp. 295-306, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[95] Prashanth Kumar Reddy Gillela et al., “A Numerical Study on Contact Conditions, Dynamic Resistance, and Nugget Size of Resistance Spot Weld Joints of AISI 1008 Steel Sheets,” *Numerical Heat Transfer, Part A: Applications*, vol. 84, no. 2, pp. 122-140, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[96] Sendong Ren et al., “Post-Weld Cold Working for Fatigue Strength Improvement of Resistance Spot Welded Joint of Advanced High-Strength Steel,” *Journal of Materials Processing Technology*, vol. 299, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[97] Sendong Ren et al., "Numerical Modeling from Process to Residual Stress Induced in Resistance Spot Welding of DP980 Steel," *The International Journal of Advanced Manufacturing Technology*, vol. 125, pp. 3563-3576, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[98] K. Reza Kashyzadeh et al., "Numerical Study of Shunting Effect in Three-Steel Sheets Resistance Spot Welding," *International Journal of Engineering*, vol. 35, no. 2, pp. 406-416, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[99] Kazem Reza Kashyzadeh et al., "Fatigue Life Analysis in the Residual Stress Field due to Resistance Spot Welding Process Considering Different Sheet Thicknesses and Dissimilar Electrode Geometries," *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 237, no. 1, pp. 33-51, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[100] Matthew Russell et al., "Comparison and Explanation of Data-Driven Modeling for Weld Quality Prediction in Resistance Spot Welding," *Journal of Intelligent Manufacturing*, vol. 35, pp. 1305-1319, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[101] Behzad Sadeghian et al., "Simulation and Microstructure Prediction of Resistance Spot Welding of Stainless Steel to Carbon Steel," *Metals*, vol. 12, no. 11, pp. 1-16, 1898. [CrossRef] [Google Scholar] [Publisher Link]

[102] Kancha Sammaiah, and Banoth Balunaik, "Investigation of the Effect of Weld Parameters of Direct Resistance Spot Welds Made on AISI C1010 Cold Rolled Carbon Steel Sheet for Auto Applications," *Proceedings of the 1st National Conference on Innovative Approaches in Mechanical Engineering NCIAME-17*, Hyderabad, India, pp. 1-5, 2017. [Google Scholar]

[103] Mohammed Helan Sar et al., "Influence of Welding Parameters of Resistance Spot Welding on Joining Aluminum with Copper," *International Journal of Applied Mechanics and Engineering*, vol. 27, no. 2, pp. 217-225, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[104] Shadab Sarmast-Ghahfarokhi et al., "The Failure Mechanism of Resistance Spot Welded Third-Generation Medium-Mn Steel during Shear-Tension Loading," *Journal of Manufacturing Processes*, vol. 79, pp. 520-531, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[105] Shadab Sarmast-Ghahfarokhi et al., "Mechanical Properties and Failure Behavior of Resistance Spot Welded Medium-Mn Steel under Static and Quasi-Static Shear-Tension Loading," *Welding in the World*, vol. 66, pp. 1609-1622, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[106] Anthony Sexton, and Matthew Doolan, "Effect of Electrode Misalignment on the Quality of Resistance Spot Welds," *Manufacturing Letters*, vol. 35, pp. 952-957, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[107] Umair Shah, "*Ultrasonically Assisted Resistance Spot Welding of Lightweight Metal Alloys*," Doctoral Thesis, The Ohio State University, 2022. [Google Scholar] [Publisher Link]

[108] Devendranath Ramkumar et al., "Microstructure and properties of inconel 718 and AISI 416 laser welded joints," *Journal of Materials Processing Technology*, vol. 266, Pp. 52-62, 20169. [CrossRef] [Google Scholar] [Publisher Link]

[109] Sumit K. Sharma et al., "Resistance Spot Welding of Aluminum 6063 Alloy for Aerospace Application: Improvement of Microstructural and Mechanical Properties," *Journal of the Institution of Engineers (India): Series D*, vol. 103, pp. 311-318, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[110] Yandong Shi et al., "Fatigue Properties of Resistance Spot-Welded Maraging Steel Produced by Selective Laser Melting," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 46, no. 7, pp. 2458-2472, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[111] Imtiaz Ali Soomro, Srinivasa Rao Pedapati, and Mokhtar Awang, "A Review of Advances in Resistance Spot Welding of Automotive Sheet Steels: Emerging Methods to Improve Joint Mechanical Performance," *The International Journal of Advanced Manufacturing Technology*, vol. 118, pp. 1335-1366, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[112] Sahand Taghavi, and Majid Pouranvari, "Spinodal Liquid Phase Separation Enabling Dissimilar Resistance Spot Welding of Immiscible Iron and Copper Alloy System," *Science and Technology of Welding and Joining*, vol. 28, no. 2, pp. 98-107, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[113] Iqbal Taufiqurrahman et al., "The Effect of Aluminum Interlayer on Weld Strength, Microstructure Analysis, and Welding Parameters Optimization in Resistance Spot Welding of Stainless Steel 316L and Ti6Al4V Titanium Alloy," *Engineering Solid Mechanics*, vol. 10, no. 2, pp. 165-178, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[114] Jiazhuang Tian, Wu Tao, and Shanglu Yang, "Investigation on Microhardness and Fatigue Life in Spot Welding of Quenching and Partitioning 1180 Steel," *Journal of Materials Research and Technology*, vol. 19, pp. 3145-3159, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[115] Cameron Tolton et al., "Investigation of Resistance Spot Weld Failure in Tailor Hot Stamped Assemblies," *International Journal of Impact Engineering*, vol. 180, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[116] Oguz Tuncel, Hakan Aydin, and Alisan Gonul, "A Parametric Study on Weld Zone Shape of Resistance Spot Welded 22MnB5 Steel," *Welding International*, vol. 37, no. 3, pp. 142-153, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[117] Abhishek Tyagi et al., "Experimental Investigation for Optimization of Robot Spot Welding Parameters on Low Carbon Steel JSC 590RN," *Materials Today: Proceedings*, vol. 51, no. 1, pp. 1211-1216, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[118] Yoshihiko Uematsu et al., "Fatigue Behavior of Resistance Spot Welded Steel Sheets Fabricated Using Electrodes with Different Tip Diameters," *ISIJ International*, vol. 63, no. 1, pp. 135-142, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[119] Ellen van der Aa, and Radhakanta Rana, "Optimization of Hot Forming Temperature to Minimize Liquid Metal Embrittlement-Induced Cracking in Resistance Spot Welded Zinc-Coated Medium Manganese Steel," *Steel Research International*, vol. 94, no. 11, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[120] Van Nhat Nguyen, Shyh-Chour Huang, and Quoc Manh Nguyen, "Investigate the Quality of the Resistance Spot Welding Joint between Aluminum Alloy and Low Carbon Steel," *Proceedings of the International Conference on Advanced Mechanical Engineering, Automation, and Sustainable Development (AMAS2021)*, pp. 52-56, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[121] K. Vignesh, "Predicting Parametric Influence of Resistance Spot Welding Process Parameters on Tensile Shear Load Using Optimization Technique," *Researchsquare*, pp. 1-21, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[122] Bingxu Wang et al., "Microstructure and Shearing Strength of Stainless Steel/Low Carbon Steel Joints Produced by Resistance Spot Welding," *Journal of Materials Research and Technology*, vol. 20, pp. 2668-2679, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[123] Hui Wang et al., "An Integrated Approach for Numerically Predicting the Failure of Resistance Spot Welds," *Science and Technology of Welding and Joining*, vol. 27, no. 4, pp. 229-237, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[124] Lei Wang et al., "Study on Microstructures and Fatigue Behavior of Dissimilar Al/Steel Resistance Spot Welded Joint," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 45, no. 7, pp. 2047-2057, 2022. [CrossRef] [Google Scholar] [Publisher Link

[125] Xiaonan Wang et al., "Zn-Induced Liquid Metal Embrittlement and Mechanical Properties of Advanced High-Strength Steel with Resistance Spot Weld," *Materials Science and Engineering: A*, vol. 843, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[126] Shitong Wei, Yiyi Li, and Shanping Lu, "Similar and Dissimilar Resistance Spot Weldability of Q&P980 and TWIP1180 Steels," *Science and Technology of Welding and Joining*, vol. 27, no. 2, pp. 77-83, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[127] Jan Wippermann et al., "Thermal Influence of Resistance Spot Welding on a Nearby Overmolded Thermoplastic-Metal Joint," *Welding in the World*, vol. 67, pp. 793-804, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[128] Rui Xiao et al., "Dissimilar Laser Spot Welding of Aluminum Alloy to Steel in Keyhole Mode," *Journal of Laser Applications*, vol. 34, no. 1, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[129] Hongli Xu, and Xiangfan Fang, "Resistance Insert Spot Welding: A New Joining Method for Thermoplastic FRP-Steel Component," *Welding in the World*, vol. 67, pp. 1733-1752, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[130] Tao Xu et al., "Effects of Magnetic Fields in Arc Welding, Laser Welding, and Resistance Spot Welding: A Review," *Advanced Engineering Materials*, vol. 25, no. 5, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[131] Fatemeh Yaghoobi, Roohollah Jamaati, and Hamed Jamshidi Aval, "Resistance Spot Welding of High-Strength DP Steel and Nano/Ultrafine-Grained IF Steel Sheets," *Materials Chemistry and Physics*, vol. 281, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[132] Yue Yang et al., "Microstructure and Mechanical Properties of 2195/5A06 Dissimilar Joints Made by Resistance Spot Welding," *Materials Characterization*, vol. 191, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[133] Zhenduo Yao et al., "Local Mechanical Characterization and Fracture Prediction Modeling for Resistance Spot-Welded Joints of Advanced High-Strength Steel," *Materials Today Communications*, vol. 36, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[134] Jiang Yu et al., "Interfacial Evolution Behavior and Mechanical Properties of Ti/steel Joint via Ultrasonic Seam Assisted Resistance Spot Welding with Cu Interlayer," *Journal of Manufacturing Processes*, vol. 95, pp. 535-550, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[135] Sang-Man Yun et al., "Improvement of Resistance Spot Weldability of Al-Fe-Alloy-Coated HPF Steel Sheets," *Science and Technology of Welding and Joining*, vol. 27, no. 6, pp. 429-436, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[136] Jiaquan Zeng, Biao Cao, and Ran Tian, "Heat Generation and Transfer in Micro Resistance Spot Welding of Enameled Wire to Pad," *Journal of Manufacturing Processes*, vol. 82, pp. 113-123, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[137] Xiaobin Zhang et al., "Investigation on Pore Formation in Pulsed Laser Spot Welding of AZ31 Magnesium Alloy," *Optics & Laser Technology*, vol. 149, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[138] Yuzhu Zhang et al., "Mechanical Behavior and Failure Mechanism of Q&P980 Steel during In Situ Post-Weld Heat Treatment (PWHT) Resistance Spot Welding," *Metallurgical and Materials Transactions A*, vol. 53, no. 3, pp. 794-809, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[139] Yixuan Zhang et al., "Microstructure and Joining Mechanism of Al/CFRTP Resistance Element Welded Joints," *Journal of Manufacturing Processes*, vol. 84, pp. 251-259, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[140] Yu Zhang et al., "Effects of Al/Zn Interlayer on the Solidification Path and Liquation Cracking Susceptibility of AZ31/ZK61 Dissimilar Magnesium Alloy Resistance Spot Welding Joints," *Journal of Manufacturing Processes*, vol. 75, pp. 60-71, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[141] Dawei Zhao et al., "Mechanical Attributes and Microstructural Characteristics of Resistance Spot-Welded HSLA 420 Steel Joints," *The International Journal of Advanced Manufacturing Technology*, vol. 124, pp. 3505-3518, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[142] Dawei Zhao et al., “Optimization of Post-Weld Tempering Parameters for HSLA 420 Steel in Resistance Spot Welding Process,” *The International Journal of Advanced Manufacturing Technology*, vol. 123, pp. 1811-1823, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[143] Linlin Zhao et al., “Mechanical Properties and Nugget Evolution in Resistance Spot Welding of Zn-Al-Mg Galvanized DC51D Steel,” *High Temperature Materials and Processes*, vol. 42, no. 1, pp. 1-14, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[144] Xilong Zhao et al., “Investigation on the Microstructure and Mechanical Properties of Stud Welded Joints of Cu/304 Austenitic Stainless Steel under Different Welding Voltages,” *Journal of Materials Engineering and Performance*, vol. 32, pp. 613-623, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[145] Baifan Zhou et al., “Machine Learning with Domain Knowledge for Predictive Quality Monitoring in Resistance Spot Welding,” *Journal of Intelligent Manufacturing*, vol. 33, pp. 1139-1163, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[146] Xian-Kui Zhu, Jesse B. Zhu, and Wei Zhang, “Data-Driven Models of Dynamic Strength of Resistance Spot Welds in High Strength Steels by Regression and Machine Learning,” *Multiscale and Multidisciplinary Modeling, Experiments and Design*, vol. 5, pp. 337-350, 2022. [CrossRef] [Google Scholar] [Publisher Link]