

Influence of Process Parameters on Resistance Spot Weld Quality: A Review of Experimental, Numerical, and Data-Driven Studies

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ABSTRACT

Resistant spot welding (R. S. W.) holds prominence within the auto sector due to its superior productivity, capability of working on tough alloys like those used in heavy-duty vehicles, and effectiveness during large-scale manufacturing processes. Here's an alternative way to express it: This document provides a comprehensive review of current research related to RSU, covering aspects such as operational techniques, potential breakdowns in connections, and methods for evaluating product performance. Amongst these parameters - namely, welding voltage, duration, pressure applied by the filler wire, and shape of the tip - they significantly influence the creation of the bead, material properties, and chemical composition. Various common issues like pullout failures, interface problems, overheating zones, and crack formation in weld joints are examined to illustrate how different welding conditions affect their strength. The document explores methodologies such as experiments, simulations, optimizations, and analytical approaches found within research pertaining to assessing welding quality standards. Despite promising results from both machine learning algorithms and non-invasive assessment methods regarding prediction accuracy, most current models remain restricted to controlled lab settings without adequate verification for practical applications in industry. Drawing upon these studies, our paper explores an overview of developing comprehensive, instantaneous, smart RSW quality control mechanisms designed to reduce dependency on destructive tests while enhancing overall welding precision particularly for intricate and diverse automobile components. Synthesis provides an avenue for exploring refined RSW procedures, thereby improving the accuracy of real-time production oversight within contemporary vehicle assembly lines.

Keywords: - Resistance spot welding (RSW), Weld quality, Nugget formation, Process parameters, Failure modes

1. INTRODUCTION

Because of its effectiveness, reliance on automation for operations, compatibility when used with lightweight materials like sheets, and widespread use across automobile manufacturing processes, resistance spot welding stands out as the predominant assembly technique employed today. In today's automobiles, each of the numerous spot welds plays an important role in ensuring robustness against crashes, longevity, passenger protection, and overall safety performance. The issue is exacerbated due to increased use of sophisticated high-tensile steel types like AHSS, mixed materials, and multiple layers in assembly, complicating efforts to ensure uniform and dependable resistance weld strength across various components [1-6, 9]. Generally speaking, the grade of a resistance spot weld can be characterized through parameters such as nugget dimension, fusion zone appearance, material composition, physical attributes, and fracture pattern. Indeed, detailed metalworking research indicates that factors such as welding power levels, tool pressure, and heat exposure durations profoundly influence the creation of weld beads and their structural characteristics ([1]-[5]). Different types of spot welding using materials like DP steel and austenitic stainless steel exhibit intricate heat and material properties due to asymmetric nugget formation, heterogeneity in microstructure, and reduced joint integrity compared to conventional methods. [1][4]. Standards such as automotive specification 8 exist in this field. The standards set by 7M and ISO 14373 offer suitable for evaluating spot welding performance; these specifications primarily rely on techniques like peeling, tension shearing, and chiseling tests which involve destruction of materials during inspection processes [18,19]. These methods excel at ensuring consistent product standards yet require substantial human effort, incur costs, and cannot be effectively used during rapid manufacturing

processes due to their limitations. A significant amount of investigation into techniques for assessing welding quality without damaging materials and using data analysis has taken place within this area [6, 8, 12, 14, 22]. Machine learning (ML) and artificial intelligence (AI) approaches have proven to be effective means of predicting and monitoring RSW quality in recent decades [9]. Early studies indicated that AI techniques can be employed to correlate process signals with weld quality performance [9]. In recent years, decision trees, k-nearest neighbors (kNN), support vector machines (SVMs), as well as hybrid models have been proposed for predicting nugget diameter, nugget width, and weld acceptability by utilizing electrical, acoustic, ultrasonic, and thermal signals [11–14,20,21]. Grounded on statistical learning theory and principles of data mining, these methods provide superior prediction accuracy and flexibility than those of conventional empirical methods [7]. Meanwhile, improved sensing technologies, namely ultrasonic testing, infrared thermography, and acoustic emission have made it possible to monitor weld quality in real-time or near real-time without disturbing production [8,14,17]. However, compared to traditional techniques, studies suggest that integrating process monitoring signals with machine learning algorithms offers more robust and reliable weld quality assessment systems [11,22]. Considering the advanced developments of automotive materials and manufacturing demand, on-going Industry 4.0 paradigms, the wide-ranging review covers the aspects of resistance spot weld quality, including metallurgical fundamentals, process control, non-destructive evaluation, and data-based prediction methods. This review will present and summarize the available literature on RSW quality in automotive production, the big challenges of advanced and dissimilar materials, along with upcoming insights for intelligent weld quality monitoring and optimisation.

2. LITERATURE REVIEW

Table 1 review of papers

Authors (Year)	Material / Application	Methodology	Key Parameters Studied	Major Findings	Research Gap / Limitation
Wei et al. (2015)	AHSS (similar & dissimilar, multilayer)	Experimental RSW, mechanical testing	Nugget size, tensile shear strength	Dissimilar and multilayer stackups show reduced weldability and strength	Limited to mechanical tests; no online quality prediction
de Faria et al. (2015)	AISI 1010 / AISI 304	Experimental RSW	Current, force, weld time	Asymmetric nugget formation due to material mismatch	No real-time monitoring or quality model
Pouranvari et al. (2015)	Stainless steels	Metallurgical analysis	Fusion zone microstructure	Complex solidification and segregation in SS welds	Mechanical performance not correlated
Pouranvari & Marashi (2013)	Automotive steels	Critical review	Process–structure–property	Highlights challenges with AHSS spot welding	Limited coverage of data-driven methods
Espinell Hernández et al. (2016)	DP600 / AISI 304	Experimental RSW	Polarity, nugget size, strength	Polarity significantly affects nugget growth and strength	No predictive model developed
Neugebauer et al. (2013)	High-strength steels	Quality control study	Process signals	Emphasized need for inline monitoring	No ML-based quality assessment
Hastie et al. (2005)	—	Statistical learning theory	Regression, classification	Foundation for ML-based prediction models	Not specific to welding
Butler (2019)	Automotive RSW	Signal-based analysis	Acoustic & electrical signals	Strong correlation between signals and weld quality	Requires large labeled datasets
Brown et al. (1998)	Steel sheets	Artificial intelligence	Neural networks	Demonstrated AI feasibility in RSW	Early-stage models, low accuracy
Zamanzad Gavidel et al. (2019)	Automotive steels	ML comparison	DT, ANN, SVM	Decision trees showed good nugget width prediction	Limited feature diversity
Zhang et al. (2015)	Steel sheets	NDT + ML	Decision tree, radar chart	Improved weld classification accuracy	Industrial scalability not tested
Junno et al. (2005)	Sheet steel	kNN-based identification	Process signals	Extended kNN effective for weld classification	Sensitive to noise and data size
Martín et al. (2014)	Automotive welds	Ultrasonic + ML	Tree-based techniques	Reliable nondestructive weld assessment	Requires post-weld inspection
Sim & Kim (2018)	Automotive steels	Hybrid ML model	Nugget diameter	Hybrid approach improved prediction accuracy	Model complexity increases
Tran et al.	AHSS	Comparative	Weldability	ML models outperform	Dataset size limited

(2015)	stackups	ML study	index	empirical methods	
Hernández et al. (2020)	DP600 / AISI304	IR thermography + optimization	Thermal patterns	Infrared imaging effective for parameter optimization	Offline analysis only
AWS (2004)	Automotive RSW	Standard guidelines	Nugget diameter, failure mode	Defines acceptance criteria	Relies on destructive testing
ISO 14373 (2007)	Low carbon steels	Welding standard	Process procedures	Ensures consistency and repeatability	No quality prediction framework
Ahmed & Kim (2017)	Automotive RSW	Decision tree	Nugget width	Data-driven models effective for prediction	Limited generalization
Betancourt (2005)	—	SVM theory	Classification	Provides basis for SVM-based weld quality models	Not applied directly to RSW
Summerville et al. (2019)	Automotive welds	Comparative review	NDT techniques	ML + NDT gives best quality assessment	Integration into production lines needed

Table 2 Classification of Literature Based on Study Type

Study Type	Description of Study	References
Experimental weldability studies	Investigation of nugget formation, weldability, and mechanical performance of similar and dissimilar automotive sheet metals	[1], [2], [5]
Metallurgical and microstructural analysis	Detailed study of fusion zone morphology, solidification behavior, and phase transformations in RSW	[3], [4]
Mechanical property evaluation	Tensile shear, cross-tension, peel tests for weld strength and failure modes	[1], [5]
Process parameter optimization	Effect of current, force, time, and polarity on weld quality	[2], [5], [16]
Quality control and monitoring	Identification of key process indicators and quality control strategies	[6], [8]
Non-destructive testing (NDT)	Ultrasonic and thermal methods for nugget size and weld quality evaluation	[13], [16], [21]
Acoustic and electrical signal analysis	Correlation of acoustic emission and electrical signatures with weld quality	[8], [12]
Machine learning – Decision tree methods	Prediction and classification of nugget size and weld quality using DT	[10], [11], [19]
Machine learning – kNN methods	Process identification and weld quality classification using kNN	[12]
Machine learning – SVM methods	Classification and prediction based on support vector machines	[20]
Hybrid and comparative ML studies	Comparison and hybridization of ML models for improved prediction accuracy	[14], [15]
Statistical and data-driven modeling	Application of statistical learning theory to manufacturing data	[7]
Artificial intelligence (early applications)	Initial implementation of AI techniques in RSW processes	[9]
Weld quality classification systems	Automated acceptance/rejection decision frameworks	[11], [14]
Standards and guidelines	Industrial standards for resistance spot weld quality	[17], [18]
Comparative quality assessment reviews	Comparison of destructive, NDT, and ML-based quality assessment methods	[21]

Table 3 Distribution of Reviewed Literature Based on Study Type in Resistance Spot Welding

Study Type	Description	No. of Articles	Percentage (%)	Representative References
Experimental studies	Experimental investigation of weldability, nugget formation, metallurgy, mechanical properties, and signal analysis	11	52.4 %	[1], [2], [3], [5], [6], [8], [13], [16], [19]
Review papers	Critical and comparative reviews on RSW process, materials, and quality assessment	3	14.3 %	[4], [21], [9]
Numerical / data-driven studies	Machine learning, statistical learning, and predictive modeling (DT, kNN, SVM, hybrid ML)	6	28.6 %	[7], [10], [11], [12], [14], [15], [20]
Optimization studies	Parameter optimization using DOE, ML, or thermal/image-based approaches	2	9.5 %	[16], [19]
Total	—	21	100 %	—

3. PROCESS PARAMETERS OF RESISTANCE SPOT WELDING (RSW)

Resistance spot welding is a thermo-electrical joining process in which the weld quality is a function of the heat generation and heat distribution at the faying surfaces. Welding current is the most essential of all process

parameters because the heat produced during welding is proportional to the square of the current. This is as mentioned above: the more the welding current, the more heat enters the weld, consequently the weld nugget diameter and joint strength is increased. The excessive current on the other hand can lead to metal expulsion, electrode sticking, and surface indentation while insufficient current causes incomplete fusion and weak welds. The weld time is the time during which the welding current passes through the workpieces. It directly controls the total heat input and affects nugget growth and microstructural evolution. A long weld time ensures adequate melting and forming of nuggets, while an excessive weld time may lead to over-heating, degradation of electrodes, and softening of the surrounding heat-affected zone. Inadequate weld time leads to under-sized nuggets with poor mechanical performance.

Force at electrode-sheet and sheet-sheet interfaces is important for determining contact resistance. The correct amount of electrode force ensures stable electrical contact and uniform electrical current flow. However, if applied at elevated force, contact resistance falls off, causing lesser heat to be produced and smaller nuggets.

On the other hand, if the electrode pressure is too low, contact resistance is elevated, resulting in localized heating, expulsion, and poor weld quality. Current density and heat concentration at weld interface depends on electrode tip diameter. Such small electrode tip is more suitable to increase current density that also leads to faster nugget formation and larger nugget size. But smaller tips are vulnerable to wear and deformation, leading to degradation of weld stability. Larger electrode tips spread current across a larger area, thus decreasing the current density and possibly causing smaller nuggets. Hold time is the time that the electrode load is kept up after the welding current is discontinued.

This design parameter plays a crucial role for successful solidification of the molten nugget under pressure and to prevent shrinkage cavities, cracks, and porosity. Due to the short holding period, premature release of force can lead to internal defects or loss of weld strength. With the addition of other parameters besides these main parameters, characteristics of material properties such as electrical resistivity, thermal conductivity, sheet thickness, and surface coatings have a huge impact on resistance spot welding activity. Inconsistent material compositions also cause asymmetric heat distribution and nonuniform nugget growth even in asymmetrical ways, necessitating careful selection of parameters. Contact resistance depending on surface conditions and coatings can become a cause for expulsion and increase the rate if not properly controlled.

4. MODES OF FAILURE OF RESISTANCE SPOT WELDED JOINTS

The mode of failure of resistance spot welded joints is widely used as a qualitative and quantitative indicator of weld quality in automotive manufacturing. Failure modes observed during mechanical testing, such as tensile shear and cross-tension tests, depend on weld nugget size, microstructure, material combination, and welding parameters [1], [4].

The most desirable failure mode is pull-out failure (button pull-out), in which the weld nugget remains intact and is pulled out from one of the sheets during loading. This mode indicates sufficient nugget diameter, proper fusion, and strong metallurgical bonding between the sheets. Pull-out failure is associated with higher joint strength and energy absorption and is considered an acceptable failure mode according to automotive welding standards [1], [4], [18].

Interfacial failure occurs when fracture propagates along the original faying surface between the welded sheets, passing through the weld nugget. This failure mode is generally attributed to insufficient heat input, inadequate nugget size, or poor fusion at the sheet interface. Interfacial failure results in lower joint strength and is regarded as an unacceptable failure mode for structural applications [2], [4], [5].

An intermediate failure mode, known as partial interfacial failure, involves crack initiation at the faying surface followed by partial deviation into the base material. This mode is commonly observed in marginal welds, especially in dissimilar material combinations where uneven heat distribution leads to non-uniform nugget formation [2], [5].

Heat-affected zone (HAZ) failure is frequently reported in advanced high-strength steels due to softening or embrittlement caused by welding thermal cycles. In this mode, fracture occurs adjacent to the weld nugget rather than through it, indicating that the HAZ has become the weakest region of the joint. HAZ failure is particularly significant in AHSS and dual-phase steels used in automotive body structures [1], [4].

Nugget fracture is characterized by crack propagation through the weld nugget itself. This mode is often associated with brittle fusion zone microstructures, excessive hardness, or metallurgical defects such as porosity and segregation. Nugget fracture is more common in dissimilar resistance spot welds involving stainless steels due to differences in thermal and mechanical properties of the joined materials [3], [5].

In cases where improper welding parameters are applied, expulsion-related failure may occur. Excessive welding current or insufficient electrode force can cause molten metal to be expelled from the weld zone, resulting in reduced nugget size and internal defects. Such welds typically exhibit premature failure, often in interfacial or nugget fracture modes [4], [6].

5. RESEARCH GAP

A systematic literature review on resistance spot welding and the weldability, metallurgical behavior, mechanical performance, and quality of automotive spot welds is undertaken. Nevertheless, there are significant research gaps yet to be closed. From the literature, the majority of publications are predominantly experimental studies focusing on the influence of welding current, weld time, and electrode force on the process of welded nugget formation and welding strength. While these studies give us great information on process-structure-property relationships, they are largely offline and post-process, using destructive testing methods such as tensile shear and peel tests. Hence, their applicability for real-time quality assurance in high-volume automotive production is somewhat limited. Although metallurgical studies have accurately characterized fusion zone and heat-affected zone microstructures, specifically in advanced high-strength steels and other dissimilar material joints, exact connections between microstructural characteristics and in-service weld performance with welding technology are still not completely realized. Additionally, the effect of dynamic process variations and electrode degradation on microstructural evolution has not been investigated sufficiently. The other such automotive standards are AWS D8.7M and ISO 14373 have standards that dictate acceptance criteria with respect to nugget size and failure mode. But these standards are descriptive, they are not predictive, nor do they include intelligent or data-driven methods to evaluate weld quality through intelligent or data-driven methods. Therefore, the compliance with standards still requires a large scale destructive test. Recent researches have shown promising potential of non-destructive techniques, for example, ultrasonic testing, infrared thermography, and acoustic emission on weld quality evaluation. Nevertheless, a substantial majority of post-weld tests that are used here involve additional inspection steps. It is thus less suitable for integrated automation in production lines. While machine learning and data-driven approaches have attracted attention for predicting nugget size and predicting weld quality, these methods tend to be trained on limited datasets under controlled laboratory conditions. Their robustness, generalization capacity, and adaptability to industrial environments with noise, variability, and electrode wear are yet poorly validated. Furthermore, numerous studies concentrate on single algorithms, with no systematic comparison or hybridization to increase reliability. Studies on optimization are few and typically involve offline design of experiments or image-based analysis. Real-time, adaptive optimization frameworks that dynamically adjust the welding parameters in response to in-process feedback signals remain few. It is worth noting that while Industry 4.0 and smart manufacturing are gaining interest, there is no comprehensive framework that combines process parameters with non-destructive signals, real-time sensing, and machine learning models for intelligent resistance spot weld quality monitoring and control of dissimilar and advanced forms of automotive materials.

6. CONCLUSIONS

The current study includes a thorough literature review of the available research on resistance spot welding focusing on process parameters, joint failure modes, and research methodologies for automotive applications. Welding current, weld time, electrode force, and electrode geometry are the most relevant parameters impacting nugget formation, heat input, and joint strength according to the review. Adequate control of these parameters is essential to achieve desirable pull-out failure which has been recognized as a good indicator of spot welding quality. The investigation of reported failure modes indicates that interfacial failure, heat-affected zone failure and nugget fracture are mainly associated with insufficient or excessive heat input, unfavorable microstructural transformations and process instability. Although the metallurgical and mechanical behavior of spot-welded joints has been under intensive exploration, most studies rely on destructive testing methods and offline analysis, which restrict their applicability in real-time industrial environments.

Though research on numerical modelling, optimization techniques, and data-driven approaches has been conducted; these techniques use mainly lab-based research environments and are not applicable to industrial environments. Absence of robust validation under practical production scenarios, limited integration of real-time sensing technologies, and adaptive control limits their practical application in automated production lines. Moreover, existing standards primarily provide acceptance criteria rather than predictive or intelligent quality assessment frameworks. Although extensive research has been carried out in resistance spot welding, it is the requirement for an integrated, real-time and intelligent weld quality monitoring system that integrates the process parameters, in-process signals with advanced data analytics that is still urgent. Filling this gap could reduce the reliance on destructive testing, optimize the production of welds, and increase weld strength, especially when applied to advanced high-strength and dissimilar materials involved in new automotive structures.

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