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REVIEW ARTICLE - MECHANICAL ENGINEERING

Vibration Analysis of Resistance Spot Welding Joint of Similar Metals (Carbon Steel AISI 1005): A Review

Osamah Sabah Barrak[1*], Slim Ben-Elechi[1], Sami Chatti[1]

[1]National Engineering School of Monastir, University of Monastir, LGM, ENIM, Avenue Ibn-Eljazzar, 5019 Monastir, Tunisia

[*] Corresponding author E-mail: usamah.barrak@yahoo.com

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Abstract

The resistance spot welding (RSW) technique is widely used for joining two or more metal sheets by involving heat generated by electrical resistance. Due to its efficiency and cost-effectiveness, it is commonly utilized in the automotive, aerospace, and manufacturing industries.
Despite its advantages, RSW faces several challenges, including inconsistent joint quality, surface defects, and variations in mechanical strength. These problems are often attributed to welding current, welding time, electrode wear, and heat distribution inconsistencies, which can compromise the structural integrity of welded components.
Various advanced processes have been developed to address these problems, including numerical modeling, real-time monitoring systems, vibration analysis, and machine learning-based optimization. These methods enhance weld quality, detect defects early, and optimize welding parameters for improved performance.
This study examines the vibration characteristics of resistance spot welds in carbon steel AISI 1005. It employs experimental and numerical approaches to analyze the relationship between vibration behavior and weld integrity. The findings are expected to contribute to developing predictive models for assessing weld quality and enhancing process reliability in industrial applications.

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Keywords: AISI1005; Vibration Analysis; Resistance Spot Welding.

1. Introduction

Resistance spot welding (RSW) is the oldest welding process of today, which is used to join two or more similar or dissimilar metals. Various studies have been reported on similar and dissimilar joints by applying various advanced technologies. The joint relationship is deeply related to various manufacturing sectors in the present cases. Regarding automation in the manufacturing sector, the resistance spot welding processes are most widely adopted in various manufacturing sectors due to their advantages. RSW is extensively adopted across various sectors for ferrous and non-ferrous materials, especially in the automobile, electrical, and electronics industries. This notable technique is favored primarily because it is quick, clean, and energy-efficient, and it does not produce harmful noxious gases during welding. The significance of this method becomes evident, particularly in resistance spot welding, where the quality of each spot weld plays a critical role in determining a workpiece's overall performance and durability. This is especially true for vehicle body components, where RSW is most commonly and widely applied. The intensification of high-strength automotive steels has prompted researchers and engineers alike to delve deeper into the intricacies of the resistance spot welding process, aiming to enhance its effectiveness and reliability. In various manufacturing industries, accurately diagnosing the quality and performance of a resistance spot weld joint presents a significant challenge, primarily due to the variability observed from spot-to-spot measurements. As a result, many companies turn to nondestructive testing methods, which are utilized to thoroughly analyze the integrity, quality, and properties of a weld joint, employing a range of different techniques. Numerous researchers have dedicated their studies to analyzing resistance spot welding across various types of steel, incorporating methods like vibration analysis to ascertain whether a resistance spot joint is experiencing failure or is in a destructive state. The discussed methodology represents a concerted effort in this direction, intended to effectively identify the status of weld joints, whether they are in a failed condition or are healthy. This identification is achieved by executing experimental and simulation results, ultimately contributing to the optimization and reliability of resistance spot welding processes in modern manufacturing practices [1-7].

RSW is a significant joining method that plays a crucial role in the automobile and aviation sectors, mainly due to its effectiveness and efficiency as a resistance spot welding technique. This method is widely utilized across these industries because it provides strong and reliable joints essential for ensuring the structural integrity of vehicles. Ensuring the body is effectively welded through the RSW process is critical to reducing vehicle weight and prolonging its lifespan. To achieve this, it is necessary to conduct a thorough analysis of the mechanical behavior of the vibrations that occur in RSW to guarantee that the welding quality meets stringent industry standards. The continual advancement in integrating sophisticated simulation techniques alongside nondestructive testing methods will enable manufacturers to analyze the integrity of the welded joints in a significantly shortened period, allowing them to predict the weld properties with greater accuracy. A limited amount of research has

Nomenclature & Symbols			
RSW	Resistance spot welding	LDCV	Low-Density Core Vibrations
AISI	American Iron and Steel Institute	HAZ	Heat-Affected Zone
PCA	Principal Component Analysis	STD	Signal Time-Domain

been dedicated to examining the vibration analysis of RSW processes involving similar metals. Given this gap in the existing body of research, a concerted effort has been made to explore the intricate effects of vibration dynamics in the resistance spot welding of carbon steel, which will be discussed in detail. Understanding the vibration mechanics in the dynamic study of resistance spot welding is a crucial decision criterion that greatly influences material design and the development of practical spot weld joints. This exploration will advance our understanding and enhance practical applications in industrial settings [1-4].

The mechanical properties of welding joints play an essential role in the fatigue life assessment of weld structures. Vibration signals during RSW have been presented as having the potential to monitor weld-joint quality and detect variations during weld upset, such as electrode wear. The three distinct stages occurring during the RSW process can each be identified from a sudden increase in the vibration amplitude. Several studies of the RSW process and its characteristics are presented, mainly focusing on measuring the normal fluctuating contact resistance during welding. The effect of welding current pulse variables on the vibration has not been identified. The changes in the contact resistance and surface conditions are considered complex non-uniformities in the RSW process that are difficult to study. Electromagnetic riveting is used to compare with RSW. It is used because electromagnetic riveting has high vibration and operates in similar RSW ranges, i.e., above 50 Hz [8-10].

This work aims to develop a systematic methodology to understand vibration transmission and enhance joint quality during welding, both with and without a weld cycle. The study will assess vibration levels, weld strength, and micro-hardness at different vibration frequencies and welding currents. It will explore how the combined effects of vibration and welding parameters impact weld strength and hardness. Additionally, the research will examine the potential of using accelerometers or Low-Density Core Vibrations (LDCV) for empirical correlations in resistance spot welded joints. These correlations can help predict weld quality online, contributing to smart RSW component development.

This study investigates the impact of vibrations on the weld strength of resistance spot welds under static conditions. It includes designing algorithms for detecting cracking force and vibration frequency using welding current and developing a monitoring system for weld rupture with a Liquid Contact Dynamic Force Sensor. Additionally, it examines vibration spectra during welding cycles and develops Artificial Neural Network and Fuzzy Logic Models for real-time monitoring of weld quality in mild steel butt welding.

2. Resistance Spot Welding (RSW)

The resistance spot welding process is a thermodynamic process, wherein large heat is generated across the high electrical resistance located at the mating interface. The localized heating for a very short duration, owing to a very high magnitude of current and pressure, produces a molten welding nugget. The joining depends on various parameters such as welding current and time, electrode material, force applied, and material properties. Here, the local melt results in material property variation, such as reduced electrical resistance and thermophysical properties. A physics-based model elucidates the role of material properties during and after welding (see Figs. 1 and 2) [5, 11-13].

Welding involves distinct phases: squeeze, weld, and coherent hold. The brief squeeze phase activates the weld current, requiring sufficient power to minimize expulsion effects. These phases are time-based and independent of the welding schedule. Applications relating to weld quality, electrode design, copper interlayers, and material combinations allow for different assembly methods, relying on knowledge of material interfaces through energy dissipation. The welding cycle addresses various interactions, including electrical characteristics and thermal properties, shaping the domain. Key behaviors like electrocalorimetric effects, heat loss, and linear resistance are discussed [14-16].

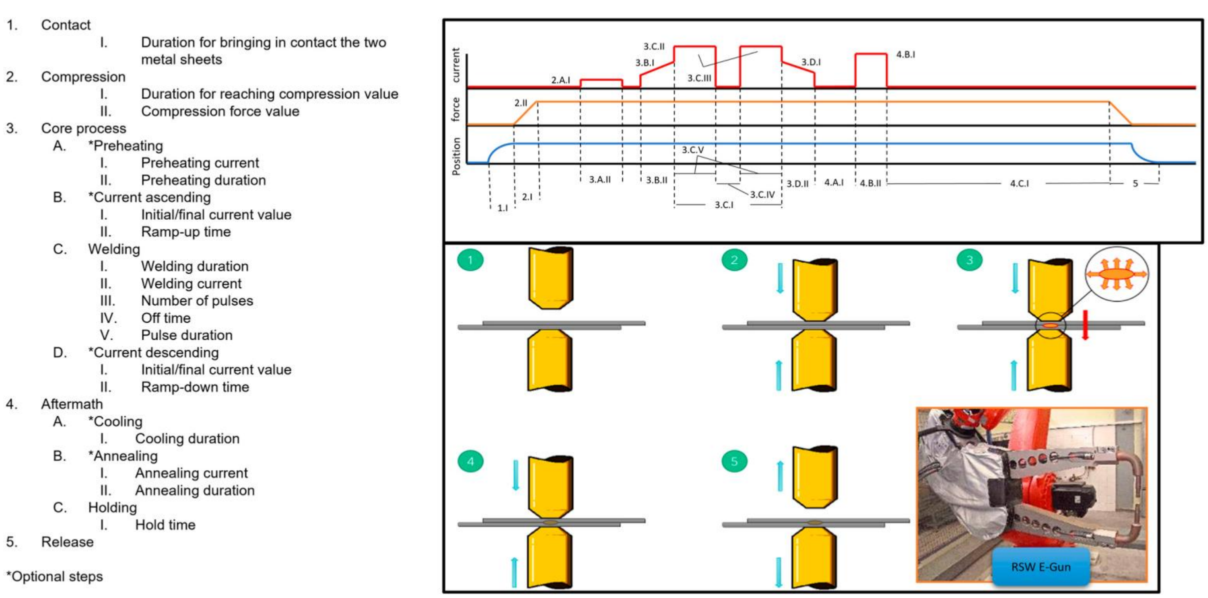

Fig. 1. A schematic representation of the RSW process [11]

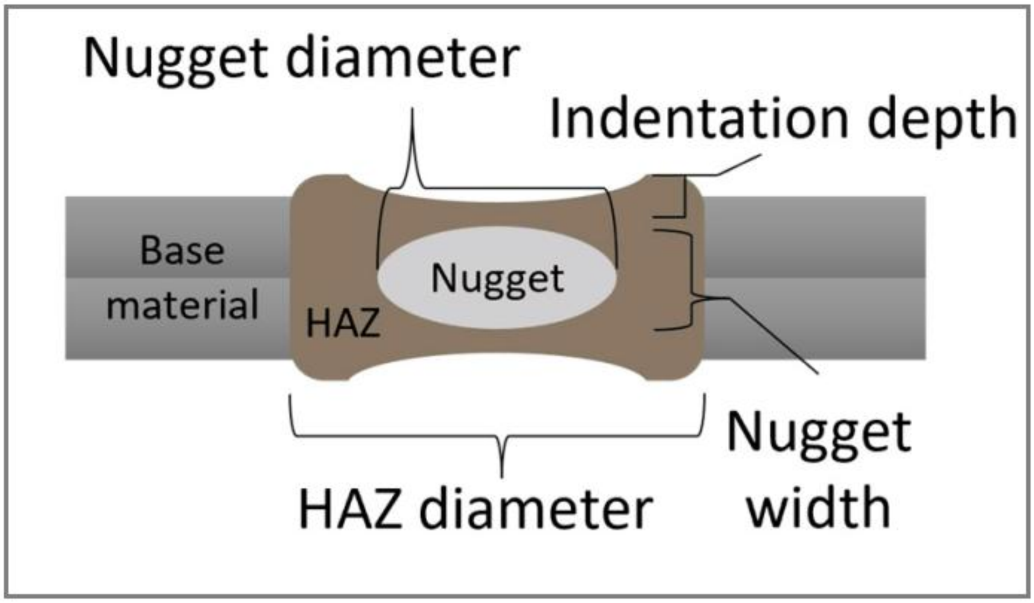

Fig. 2. Schematic of joining zone's geometrical features [11]

2.1. Welding parameters

Resistance spot welding uses several parameters to make the joint. These parameters significantly affect the quality of the joints as well as process performance. Welding parameters used in RSW are welding current, electrode force, weld time, and cooling rate. These parameters have been related to the quality of the joint, and equations that describe them exist. In resistance spot welding, close control of all four major welding parameters is inherent to producing good joints. However, unspecified ranges of these welding parameters may not produce good-quality welds. The relationship between the welding parameters and the type of joint may become less favorable if the process moves outside the design envelope. Monitoring the welding parameters may interrupt the process between welds, causing an unproductive offline inspection [17-19].

Standard welding practice involves adopting a single range of welding parameters that are valid for producing the right quality of welds in a specific group of components made of similar materials. Applying these welding parameters for welding different materials and welding conditions is a serious problem. Therefore, a particular set of welding parameters is developed to produce good quality welds using this unique range of welding parameters, and it is expected that this may initiate little or no defects in the weld joints. The process's overall success is beneficial for users, manufacturers, and consumers [20-22].

2.2. Advantages and applications

Due to its rapid and non-critical advantages, resistance spot welding is considered a difficult-to-beat process and is widely used in high-volume production. RSW offers advantages in welding speed and efficiency. Automation in RSW is easy to adapt due to its induction of electric current to melt and join faying surfaces quickly. Spot welding offers a clean exit, producing finished welds with a smooth surface. Because RSW is a non-fusion welding technique, it does not require filler material. The process is one of the fastest welding practices in which automatic machines operate for even a few tenths of a second. RSW is, therefore, essential for joining materials. The demand is mainly for metal-to-metal applications. Over 60% of the work is welding ferrous metals and their alloys [23-25].

RSW is effective when using similar materials, offering strong connections. Various resistance spot welding techniques indicate that compositions can be similar or dissimilar metals. Primarily, RSW is ideal for welding metals with similar properties. For instance, Carbon AISI 1005 steel, a low-carbon variant, is suitable for similar applications. RSW can be applied vertically, horizontally, and in angular joints. The minimum wire tensile failure force was recorded through twelve experiments at 35 kN, with a maximum of 43 kN at specific machine settings and a constant 8-second welding time. Single-lap joints exhibit greater tensile failure forces than low-carbon steel joints. RSW allows for detailed testing of joint thickness, displaying slight ductile-brittle failure. The tensile strength of RSW, determined via an ultimate tensile strength test, varies with nugget diameter and can span 25% to 35%. RSW finds extensive applications across industries, including automotive, aerospace, marine, electronics, and domestic sectors. Research efforts focus on reducing weldment response through vibration analysis, alongside enhancing weld penetration in this thermo-mechanical process, especially amidst energy shortages and global warming concerns [5, 26, 27].

3. Principles of Vibration Analysis

The vibration theory, rooted in mechanical systems, can explain vibrations in spot welding, where localized heating at interface resistance occurs. This resistance leads to brief high-expansion, high-pressure conditions that release heat. The timing of this pressure release happens at metal surface interfaces and within the metals themselves. The resulting vibrations illustrate the interface behavior, impacting joint mechanical quality and reliability. Each mechanical vibration system has specific frequencies and amplitudes concerning its machinery. The joints' displacement amplitude is highest for similar metals at temperatures up to 0.6 Tm and 3300 Hz; dissimilar joints vary with the thinner metals' properties. Electrical resistance drops with vibration at high frequencies, while in kHz, it decreases as melting starts. Solid metals show higher damping with restricted vibrations, and stiffness varies with material properties and states. Joint behavior, stiffness changes, and damping with temperature can indicate automotive spot weld integrity. Vibration can be detected using sensors mounted on weld heads, with microsensors for detailed analysis. Monitoring vibration activity helps identify joint behaviors, heat-affected zones (HAZ), and material states during cooling. In spot welding dissimilar materials with lower hardness, breakage is more common, revealing specific material vibration characteristics. Advanced micrometers for real-time vibration studies integrate hardware and modern software tools [28-30].

3.1. Vibration Analysis of RSW Joints

Vibration Analysis of RSW Joints is an area of application of Vibration Analysis other than industrial robots. Vibration Analysis is a technique that is extensively used for monitoring operations. Detection of destruction, ripple formation, plastic deformation, disintegration or discontinuity in a part, microvoid generation, crack propagation, wire rupture, dissimilar metal weld, porosity, and uniform mushing of heat or other defects are some of the applications of Vibration Analysis. There is a need for regular maintenance, process monitoring, and control in RSW. Therefore, vibration signals that control the welding conditions and the motion of the electrodes are already used to examine the weld quality in the RSW process [31-33].

Research on weld defects due to dynamics has made significant progress. Vibration waveform analysis has proposed countermeasures for high-frequency weld defects. A new approach is required. The study of the applicability of online signal processing methods in RSW has contributed to the understanding of RSW tuning. Many reports focus on how RSW vibration signals can explain the vibration analysis methodological archetype and how the signal is to be obtained during RSW welding. Some inconsistencies in extant literature underlie the characterizations of the vibrational signals and how they relate to the tuning characteristics. Examples of the most supporting studies show interesting results systematically when discussing such analyses. Although an interpretation of the vibrations has not been completely manifested, the nature of contact and vibrational potency is often characterized [34-36].

3.2. Importance and benefits

Vibration analysis in resistance spot welding is used effectively to improve weld quality and minimize defects. Spot welding is the most efficient, flexible, and volumetric process for car body panels. Unexpected failures during the welding process can result in production downtime and increased operational costs. Despite its simplicity, resistive spot welding must be used effectively to avoid premature part fatigue failure. Vibration analysis of resistance spot welding using the accelerometer at fixed impedance has been shown to neutralize disturbing impacts and increments. The distinct advantages of using vibration analysis in resistance spot welding of dense electrolytes include differentiating between defective and non-defective weld times, mainly with some distortions. Economical quality estimates, such as improving scrap rates and reducing rework, have improved welding processes. The main merit of this evaluation is one additional method for the maintenance of predictive assembly. Many preventive mechanisms have been established to identify the possibility of breakage in the remaining applicable life plan. Vibration signals in resistance spot fusion are primarily used for online and offline monitoring. The accelerometer is essential for detecting the same soft increase in welding electrode sensors; such a vibrating technique used in soft-threaded coil resistance welding is highly effective in estimating the weld boundaries between good and bad qualifications, regardless of flat or positioned joint settings. Long-term trend vibration analysis plots can be reevaluated with a die-life perspective. The overall peak sound level of the seam weld begins to stabilize during radiographic evaluation. It serves as an input with the electrode performance of the crown disk effect in spot welding joints [33-37].

3.3. Techniques and methodologies

Vibration analysis using special sensors, generally accelerometers and piezoelectric sensors, is integrated with data acquisition systems. Shearography measures the evolution of temperature distribution during resistance spot welding. It is concluded that by using shearography, an accurate temperature measurement over the process time is possible. The state of the art in laser welding, especially with thin sheet metals, is that a scanning speed of 100 mm/s produces the best Vickers hardness. Principal Component Analysis (PCA) based on attribute data can process vibration acceleration features on low-carbon steel surfaces contaminated during the normal production engineering process by a layer of cooling lubricant [38-40].

Four analytical techniques, time-domain, frequency-domain, modal, and wavelet analysis, are used to study dynamic data. The choice of method depends on the nature of the problem and the required results. Frequency-domain analysis in welding assesses the welding force, energy per point, strength, and weld life. This analysis is implemented via the Fast Fourier Transform to maximize the power function. However, welding force transfer indicated no frequency-related vibration alterations, suggesting a defective short circuit. The time-domain analysis involved six tracking signals, which were analyzed in detail in a case study, highlighting concerns about the adequacy of Signal Time-Domain (STD)-based methods in identifying electrode wear in RSW. The tracked signals include welding current, electrode displacement, welding pressure, voltage, force in the electrode system, and bypass voltage. Any presented STD evaluation method aids fracture mode classification or RSW quality evaluation. [41-43].

So far, reports have relied on proprietary or omitted lab test data for analysis, which, while helpful in understanding process technology and model coefficients, often diverges from manufacturing data. Caution is required when using these lab results. A comprehensive methodology for acquiring vibration data without extra noise is lacking in automotive manufacturing. It should also identify vibration sources, such as welding timers and nearby water. Furthermore, a method for data management, transformation, extraction, and interpretation of vibration signals during welding processes is absent. Current auditory and vibratory signal administration methods are limited, with few calibration techniques available. By comparing results and recommendations from various approaches, overall improvements in the welding process can be achieved [44-46].

4. Similar Metals Welding

With the growing demand for product design, the requirement for welding has increased. One of the standard requirements is the joining of different materials. Technological advances focus on joining components made from dissimilar materials. However, the fabrication of similar welding materials, such as resistance spot welding of three layers, is also essential. Carbon steel 1 mm thickness is widely used for automobile manufacturing. Carbon steel AISI 1005 is a crucial electrode material. Temperature distribution during welding of any material is influenced by its thermal properties, such as thermal conductivity and specific heat, and physical properties, like elastic moduli and melting point. Since the exact atomic nature mainly governs base material plates and heat source material, welding work between similar metals is beneficial. The quality requirement in similar metal welding is more straightforward to meet than in the resistance spot welding of dissimilar metals. Therefore, it is essential to improve spot welding of similar metals AISI 1005 [47-49].

During spot welding, two main processes play an essential role: the formation of joints and the thermal process, which converts electrical energy into heat energy. In spot welding, good joint formation is attained when there is minimal external contamination, and both surfaces are sufficiently cleaned to ensure that flash formation occurs, which helps remove non-metallic materials. About 20% of the total input energy is utilized for electrode wear during chain wheels and similar welds with low melting point electrodes. Hence, there is more wear in high-strength steel and similar metal welding since the heat dissipation at the surface and pulse duration necessitate a higher force for the electrode. The contact resistance has a strong influence on the temperature distribution during welding. Electrode wear is reduced due to the shorter duration of welding. The surface condition is also mainly necessary, and improvement can be achieved by pre-weld and post-weld surface finish. The above facts prompted us to optimize the welding parameters to establish the welding range and produce a uniform nugget area for industrial utilization. This can lead to establishing better welding conditions optimized to yield joints of maximum welding quality. The present paper deals with an overview of welding two identical metals subjected to vibrational analysis and its associated challenges [50-52].

4.1. Carbon Steel AISI1005 characteristics

The chemical composition of AISI 1005 includes 0.06% carbon, 0.35% manganese, 0.04% phosphorus, 0.07% sulfur, and 0.01% nitrogen. This low carbon equivalent makes the material weldable by resistance and arc welding, and the other constituents, such as manganese, contribute to the microalloying of the HAZ, making the AISI 1005 steel a good option for welding. Regarding mechanical properties, a maximum tensile strength of 9.1051 was found in the tensile tests. Due to the lower carbon content, AISI 1005 offers a higher level of ductility, especially at low strains, making sheet metal made of this steel much easier to form and shape. Two rolling techniques were observed for reducing the dislocation density: ferrite laminae and equiaxed ferrite grains. Resistance spot welding is a suitable method for the AISI 1005 steel sheet, showing good weldability and strengths similar to the base material, such as electrode pressure ranging from 0.4 to 10 kN, welding force from 0.060 to 0.109 kN for aluminum-based electrodes, and 0.095 to 0.132 kN for copper-based electrodes, welding times varying from 3 to 10 cycles, and weld currents ranging from 0.35 to 17 kA [53-55].

With AISI 1005, incomplete welds for some welding parameters have been observed because the lack of bead formation is directly influenced by the base material's hardness and the shape and dimensions of the electrodes used. When insufficient heat is applied, the weld integrity is not established, resulting in a lower weld cross-sectional area and inadequate current. In resistance spot welding with mild steels, various welding parameters such as current, electrode force, and welding time can lead to various performance results. Some variations in the weld cross-sectional area for AISI 1005 similar joins, in which the fusion zone itself is influenced by the level of the heat input, depth to width of the beads, and a deeper profile of the fusion crater. Several electrode forces, forming lower and higher current values, result in a difference in the tensile shear strength. Consequently, both substrates were welded by varying the welding force. A change in hardness was observed, demonstrating that substrate one showed a higher welding ability than the second one because higher hardness values were determined [56-58].

4.2. Challenges and considerations

Welding similar metals is always a challenge regarding joint efficiency and weld consistency. The carbon steel AISI 1005 is widely preferred for shear applications in the automotive industry. The welding of similar metals produces low-strength intermetallic phases, which reduce joint efficiency and weld reliability. The thermal effects and metallurgical phenomena lead to erratic and inconsistent weld quality. The weld strength of resistance spot welding of similar metals is lower than that of dissimilar metals. The wires of base metals are in the alpha range, and at the weld nugget, in the delta and gamma ranges due to direct Joule heating. Thus, α-Fe, α-Fe3C, and δ-Fe are present in the weld zone under different electrical energy inputs. Generally, weldability is checked according to cross-weld tensile testing [51, 59, 60].

The pointed electrode tip needs to be replaced after a certain number of welding cycles due to sudden degradation, such as balling, mushrooming, pitting, spalling, and melting. This affects the quality and productivity involved in spot welding. The degradation of the electrode tip leads to adjustments in the welding parameters, such as welding current and welding cycle time. Multiple experiments are required to optimize welding parameters. The welding of dissimilar or similar metals should be thermally balanced to avoid defects. The thermal balance in the welding cycle of resistance spot welding of dissimilar or similar metals cannot be achieved due to electrode degradation. The cleaning process affects weld quality, and for proper insulator removal and effective cleaning, the top electrodes should be designed accordingly. The explosives formed due to the dusty electrode surface may affect the resistance spot welding of similar metals that interact with the top surface of the marketing plate. The galvanized layer has good resistance to rust due to zinc, but ultrasonic cleaning is suggested for a clean and better weld interface. The weld parameters interact with similar metals, and optimization makes the resistance spot weld of similar metals defect-free and capable of further loading conditions [61-63].

5. Literature Review

This paper reviews and critically investigates the current state of the art regarding vibration analysis, specifically in RSW for similar metals. Numerous studies have explored the relationship between vibration analysis and various welding parameters, aiming to optimize this crucial process across various applications. Vibration has been established as a vital parameter for achieving high-quality welding in all research investigations. Both analytical and experimental models have been developed to either measure or predict vibration and several finite element models have incorporated vibration analysis into the resistance spot welding process. Generally, it is well recognized that a comprehensive understanding of the dynamic response inherent to the RSW process would lead to significant enhancements in the overall welding technique. However, there is a noticeable scarcity of publications focusing on the experimental aspects, with dynamic analyses of the weld zone being particularly limited. Various techniques utilizing vibrations have been innovated to optimize process parameters within the RSW framework. A key trend in the experimental component involves considering the dynamic behavior of the electrodes, which plays a critical role in the overall welding performance. Nonetheless, the impact of the resulting information is somewhat restricted; at this moment, it primarily reinforces the view of resistance welding as more of an art form rather than a precise science. The theory surrounding energy storage in conjunction with vibration analysis has emerged in existing literature; however, it remains to be commercially adopted and utilized effectively in practice. The resistance spot welding process is inherently dynamic and influenced by various welding conditions that impact each relevant electrical and thermal characteristic. This dynamic condition results in abrupt and considerable changes in spring constants while also causing an increase in vibration amplitude during what is referred to as the soft period as the nugget diameter increases. These observed results suggest that closely monitoring the vibrations during the soft period makes it possible to detect shifts in the diameter of the nugget within the flexible regime. It can thus be concluded that the soft period is predominantly a result of alterations in the stiffness of the nugget. Importantly, the information yielded from the welding signature, which contains valuable insights, does not directly correlate to the specific welding conditions, as is seen in parameters such as the normal force involved in friction welding. Therefore, a novel approach is necessary to address this complex phenomenon, particularly focusing on controlling thermal expansion during welding to improve outcomes [64-66].

Often, RSW welded joints fail due to poor weld quality. Vibration is one of the important factors that influence weld quality. Limited research has been done to study the effect of vibration on the RSW joint of similar metals. This section presents the prominent, influential research contributions to vibration analysis during RSW and associated developments, methodologies, and findings. Scientists have reported that the principal reason behind most of the defective welding joints in RSW is the lack of information on the behavior of the joint during the welding processes. Most joint studies use innovative nondestructive test methods such as IR cameras and laser vision under nonidentical welding conditions. An empirical relation between temperature and weld quality during welding of Ti-6Al-4V has been established. Combining different inspection techniques can be an interesting approach to assure weld quality in FRW and SRW welding processes [40, 67, 68].

The effect of vibration on the RSW of aluminum alloy 2024 was presented. Analytical heat analyses of weld nuggets were calculated and related to observe metallographic images. The weld formation delay and weld area for RW, RH, and NRH were obtained from the moment-time curves. RH in RSW was significantly decreased by increasing the friction pressure and using harmonic RSW. NT-SS showed a similar vibration pattern to conventional welding. In RSW, localized heating at the interface caused the melt initiation, which delayed the weld formation, increased the weld area, and led to severe nugget pull-out failure (see Fig. 3). Increased vibration lowered the strength and toughness of spots. The effects of vibration on the weld properties and expulsion of similar metals during RSW under normal welding conditions have been reported. Furthermore, improved precision in tensile shearing test results using developed fixtures has been disclosed. The value of tensile shear strength in spots without expulsion increased by 40 MPa following vibration during the RSW process. The 5% vibration pair of frequency and velocity increased both the load and stiffness by 11-16% in the initial stage of load transfer. These results can be considered a new perspective for optimizing the welding process [37, 38][69-71].

The monitoring of welding processes and real-time analyses of weld quality in resistance spot welding (RSW) are notably underexplored. Advanced sensors and flow-dynamic techniques to study vibration generation during RSW have not received significant attention. A multi-directional monitoring approach is essential for identifying abnormalities, yet many methods are one-dimensional. Research must focus on methodologies examining process dynamics for evaluating weld quality in automotive metals, including advanced high-strength steels with micro alloying. Furthermore, current monitoring techniques often detect issues post-event, highlighting the scarcity of quantitative, real-time monitoring methods in vibration and RSW analysis.

Advancements in sensing technologies and machine learning allow a deeper understanding of RSW vibration using historical data and real-time insights. Machine learning can aid in developing diagnostic tools to assess weld penetration depth and quality in pneumatically operated RSW. Characterizing the weld coalescence process through algorithms requires consistently gathered data under specific RSW parameters. Utilizing computational modeling like the finite element approach can enhance real-time feedback on RSW process dynamics. This leads to insights into critical variables affecting shear and peel load performance, such as the texture of the hybrid zone. Additional studies on hybrid RSW are essential due to their significance in automotive applications.

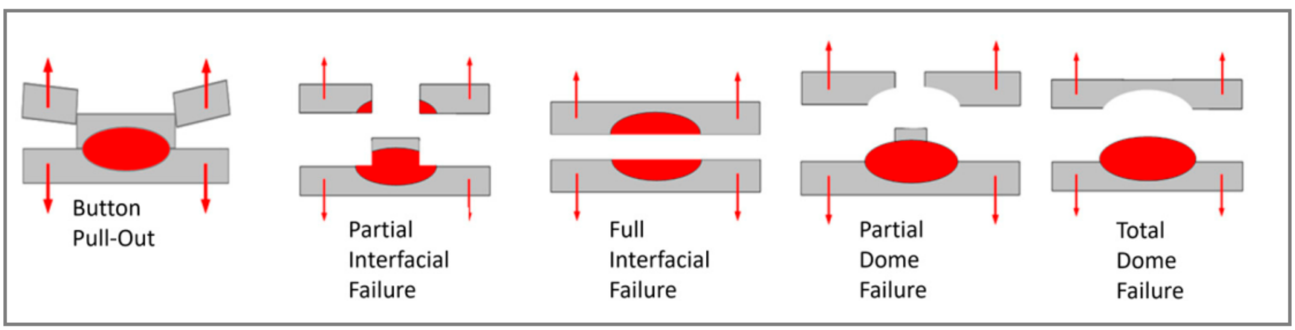

Fig. 3. Schematic representation of failure modes [11]

6. Applications and Case Studies

6.1. Applications

Over the years, several application studies have been proposed in the welding community to improve weld quality in the RSW process using vibration monitoring techniques. Vibration-based monitoring has emerged as a promising method to analyze the integrity of welded joints in real-time, detect defects, and optimize welding parameters.

The case study significantly expands upon previous research, in which the time-amplitude tolerance approach and centroid analysis were used to analyze vibration. Adopting an alternative method for effective remote monitoring of weld quality is important. Current systems do not provide clear indications of external energy generated during welding, particularly regarding the nugget formation. Additionally, data from other tools can be misleading or inaccurate. While arc sound has been a traditional method for monitoring weld quality, its relevance has declined due to concerns over energy parameters, rendering its real-time monitoring capability questionable. In contrast, vibration-based techniques offer a more detailed analysis and can be integrated seamlessly at low operational costs, enabling continuous quality monitoring. These advances evolved over conventional adjust-and-wait quality control methods commonly used in the field.

6.2. Case studies

Industries such as automotive, aerospace, and household appliances have successfully executed vibration analysis in RSW. In the automotive, real-time vibration monitoring decreased weld defects by 25%, enhancing vehicle body assembly quality. Aerospace manufacturers have employed this technique to detect micro-cracks in joints, improving component durability and lowering maintenance costs. Household appliance manufacturers acquired a 20% advancement in product durability by monitoring resistance spot welds in washing machines and refrigerators, reducing warranty claims.

These cases indicate how vibration analysis improves weld integrity, decreases defects, and optimizes manufacturing efficiency across various industries.

7. Challenges and Limitations

RSW generates complex harmonic resistance waves from the weld and its production interactions. Researchers face challenges capturing accurate data with low-frequency sensors, especially in noisy environments. Resistance forces vary due to changes in electrode geometry, the metals' properties, fluctuating process parameters, and clamping conditions. Each factor significantly impacts the spot electrode's surface characteristics during welding. Inconsistencies in electrode measurements can affect the weld's material properties and integrity. Additionally, the nugget's changing volume during growth complicates measurement accuracy and reliability. These complexities highlight the need for advanced data collection methods to ensure weld quality and dependability.

Current monitoring methods using resistance force face technical challenges that hinder detecting small operational changes, leading to high costs. Shipyard industries prefer nondestructive techniques for online and offline resistance spot welding monitoring to enhance weld quality prediction. The proposed approach is advantageous due to its requirement of a minimal mass but is limited by operational frequency and speed constraints. Data analysis in place relies on mean value and variance but lacks sensitivity to specific weld types, as existing control tools cater to continuous or batch production. Current methods cannot fully utilize advanced control under varying process conditions. A model based on force interaction with the welder allows for monitoring the force generated in the welding machine using force-sensitive resistors. However, integrating force sensors poses challenges, such as underpotential filtering caused by mechanical connections. Oversized mechanical sensors reduce accuracy due to deflection issues, necessitating high-speed data acquisition systems and amplified laboratory equipment for effective measurement and interpretation. While the costly process model enables weld quality prediction, real-time monitoring adjusts parameters based on model variations, limited by the mentioned shortcomings. Commercial sensors struggle to capture data in noisy environments, and the basic requirements for sensors must exclude extra equipment or costs beyond tooling while still providing insights on weld quality, particularly for pre-reformed structures facing significant data conditions [72-74].

8. Results and Discussion

The vibration analysis measurements, various experiments, and detailed simulations were utilized to validate whether they could accurately predict the quality of the welding joint in various contexts. The comprehensive analyses allowed for predicting various weld defects associated with different welding currents while revealing that a range of defect frequencies influenced vibrations. It was found that higher amplitude welding currents resulted in fewer weld defects when compared to lower amplitudes of welding currents, indicating a significant relationship between the welding current's amplitude and the welding joint's integrity. Further investigation into these dynamics can provide deeper insights into enhancing welding techniques.

The accumulated data collected from various welding experiments could indicate whether a weld is good or bad based on the welding responses present in the signal. This study was meant to investigate this vibration technique's extensive impact further. The comprehensive numerical study permits a detailed calculation of the welding nugget area through a one-dimensional approximation, facilitating better validation of the entire welding process. Background literature thoroughly reflects on the piezoelectric sensors utilized in the technology and joint vibration, which includes valuable data on the normal welding nugget characteristics consistently accumulated from this significant development. To validate the welding responses effectively, spot welds were made for low and high welding currents using the resistance spot welding process, ensuring a robust comparison. The signal analysis experiment results and meticulous analytical simulations of the welds were carefully conducted and subsequently validated. Each technique's performance was rigorously analyzed and thoroughly evaluated. This process demonstrates that piezo sensors were installed effectively and can provide valid early parameters for output. Moreover, they can predict further weld quality using each previous welding response, creating a comprehensive framework for quality assurance in welding [75, 76, 31].

The results observed on the micro-phase weld joints indicated that the welding current exhibited no significant differences. Upon closer examination, the welding signals captured from each welding experiment appeared to be influenced notably by the presence of defects. Furthermore, the trends identified from the various welding experiments revealed very few weld nugget defects that initiated with a higher welding current, especially compared to the number of welding nugget defects that formed during lower welding currents. Each weld produced for the different welding current levels exhibited distinct and varying responses. Moreover, the experimental results highlighted that positioning the transmitter and receiver on the piezo sensor was crucial in impacting the quality of the received signal. When comparing the galvanized and non-galvanized sheet metal welds, a notable similarity in trends was observed for each respective type of sheet metal. However, it was noted that the welding currents applied to the galvanized sheet were, in fact, higher than those applied to the non-galvanized sheets. These comprehensive tests ultimately provide valuable insight into the potential complexity and challenges associated with installing and employing such advanced techniques within the welding process. Power measurements conducted during the experiments explored how various signals correlate specifically to the characteristics of the weld joint. The findings demonstrated that a thorough re-investigation of these processes must be undertaken to successfully install any particular technique or process. It is critical to note that all techniques employed are valid for spot welding applications, and this summary effectively indicates that all can be equally beneficial in addressing and overcoming the inherent difficulties encountered throughout the welding process. These insights are essential for practitioners looking to enhance the quality and reliability of their welding operations [77-79].

9. Conclusion

This study emphasizes the importance of vibration analysis in estimating and enhancing the quality of resistance spot welding joints. While this review provides helpful insights, it is important to note that the primary findings from this investigation aim to significantly aid researchers and professionals within the welding industry in improving and enhancing methodologies currently employed in this vital field. The primary findings from this investigation aim to significantly aid researchers and professionals within the welding industry in improving and enhancing methodologies currently employed in this vital field. Previous studies and analyses have consistently shown that existing vibration analysis methodologies could be refined and optimized further. Innovative techniques that involve detailed vibration analysis and the prediction of essential mechanical properties and intricate geometrical features hold considerable potential for improvement, which can effectively address the evolving needs of the industry. This thorough analysis is critically important for accurately assessing the quality of welds, which is a primary factor that draws researchers and professionals to engage deeply in this area of study. However, it is noteworthy that this important subject is receiving limited attention within the broader context of welding techniques, underscoring the pressing need for better and more effective applications in the evolving field of welding technology. Recent and significant advancements in vibration analysis, particularly with modern technological innovations, present new opportunities for enhancing ongoing research initiatives in resistance spot welding. Furthermore, future research endeavors should strongly emphasize developing advanced instrumentation systems tailored for various applications in vibration analysis, along with its broader industrial uses.

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