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Review Article

Advancements in Resistance Spot Welding of Titanium and its Alloys: A Comprehensive Review

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Abstract - *Titanium (Ti) and its alloys have a superior combination of strength, low density and corrosion resistance, which are very valuable materials in the automotive, aerospace and medical industries. Due to its high contamination sensitivity, oxygen reactivity, and brittle intermetallic compounds, conventional fusion welding of Ti alloys is very difficult to achieve. Ti alloys provide better welds with little heat input or distortion. Therefore, Resistance Spot Welding (RSW) has emerged as a feasible method of joining Ti and its alloy sheets. Also, RSW of Ti and its alloys provides unique opportunities in welding technology. This review aims to analyze a comprehensive overview of RSW principles, fundamentals and applications in Ti and its alloys with discussions on alloy composition, surface preparation and nugget formation. This paper discusses the influence of some process parameters, including electrode force and tensile loading, welding current, sheet thickness, welding time, diameter and RSW issues and constraints. It also provides ideas for improving both performance and weld quality. This study also discusses the basics of RSW, commonly used Ti alloys, process parameter effects, key research findings and future research directions. The results obtained from the literature highlight research gaps in understanding material thickness, electrode diameter effects and the need for research on specific Ti alloys such as AMS 4902. Future research might focus on optimizing RSW for thicker sheets, determining optimal electrode sizes and examining welding behaviors of specific alloys to improve understanding and application in industrial fields.*

Keywords - *Resistance spot welding, Titanium, Process parameters, Weld quality, Process optimization.*

1. Introduction

One important method used in automotive and aerospace industries is Resistance Spot Welding (RSW) [1-3]. Approximately 2000–3000 weld locations are completed on the single-car bodies in current automobile manufacture; these weld spots are now numerically controlled. This approach is based on Joule's heating equation, which declares that the heat produced is accurately proportional to the square of the welding current [4]. RSW is an essential process in modern manufacturing known for its speed, efficiency, and reliability. Compared to other welding processes, RSW consumes low amounts of energy. RSW allows for the rapid joining of metal pieces, making it efficient for mass production in the automotive industry [5]. RSM is simpler than other welding methods, which supports train operators and reduces errors. RSW produces strong and durable joints that join thin metal sheets together. It is useful for creating spot welds in automotive body parts and other applications. RSW is involved in welding various metals and alloys, which makes it versatile across various industries. Because weight and performance are critical considerations in the automotive and aerospace sectors, RSW's versatility has led it to become one of the most widely used welding processes around the world. RSW is easily automated, which can be done consistently, accurately, and quickly. The HAZ is minimized due to the localized nature of the welding process, which confines the heat input to the region where the electrodes make contact. As a result, the distortion of the welded material is reduced. The process is low-cost in terms of equipment and operation. Its minimal material usage and high speed also contribute to cost savings in manufacturing [6]. Another important factor in its extensive use is its ability to maintain production speeds without worsening weld quality.

It uses a high current with low voltage to weld various metals such as different steel grades, Magnesium (Mg), Aluminum (Al), Copper (Cu), Titanium (Ti), and their alloys [7]. RSW typically joins thin sheets of similar or dissimilar metals in a lap joint configuration. The excellent temperature stability, strength-to-weight ratio, and resistance to corrosion of Ti and its alloys have made them desirable in various industries [8]. These properties are important for applications requiring long-term reliability under extreme conditions, such as spacecraft, aircraft components and medical implants. The RSW of Ti and its alloys have gained importance as industries aim to optimize welding processes for quality and efficiency. However, it faces several issues, such as liquation cracking, misalignment, voids and electrode wear. Welding thicker metal sheets can be challenging with RSW due to the tendency of heat to disperse rapidly into the surrounding metal [2]. Also, the high thermal conductivity of Ti alloys results in rapid heat dissipation, which can complicate the formation of stable weld nuggets in thicker sheets. These challenges need widespread surface preparation and optimization of welding parameters.

As industries increasingly demand cost-effective and high-performance joining methods, optimizing RSW parameters for Ti and its alloys becomes significant for enhancing weld quality and improving the durability of welded components. To maximize efficiency, productivity, and the quality of welds formed by Ti and related alloys, it is essential to optimize the RSW settings [9]. Proper parameter management can reduce defects such as porosity, cracks, and inconsistent welds, supporting joint durability and strength. In recent studies, key parameters important to adjusting welds to specific applications and material combinations have been highlighted: it depends on the electrode force, welding time and current intensity. Optimizing the process parameters helps control the HAZ and minimize thermal damage to the surrounding material, thus preserving its mechanical properties. Consistent application of optimized parameters leads to uniform weld quality across multiple welds, essential for mass production and quality control. Different materials and thicknesses require adjustments in parameters such as current and pressure. Optimizing these parameters ensures compatibility and optimal performance for various materials. Optimizing process parameters minimizes issues such as weld spatter and other unexpected occurrences, leading to a safer working environment. Much recent research has been explored to understand the complex interplay between material properties, electrode design and electrical parameters that develop the RSW process. Moreover, optimization can help reduce energy consumption and electrode wear, leading to improved overall efficiency and sustainability [10].

Despite the widespread application of RSW in automotive, aerospace and medical industries, some challenges remain in optimizing the welding process for Ti and its alloys. Some issues, such as liquation cracking, misalignment, void formation, and electrode wear, affect the integrity and quality of welded joints. In addition, welding thicker Ti sheets is difficult because of rapid heat dissipation, resulting in insufficient fusion and poor mechanical properties. With the increasing demand for high-performance, durable joints in critical applications, improving the understanding of factors affecting weld quality in Ti and its alloys are needed by optimizing RSW parameters.

The existing literature on RSW of Ti and its alloys is reviewed, and several limitations in the current understanding of RSW are identified. However, there are many studies focused on interlayer effects and specific Ti alloys that do not provide comprehensive analyses of RSW principles and their applications. Additionally, few studies have focused on individual process parameters, their interactions and consequent effects on weld quality and mechanical properties. However, there are gaps in practical applications for industry in key topics, such as the influence of alloy composition on the welding process. Also, previous studies are limited to discussing future research directions to advance the field. Limitations in RSW procedures and the reliability of welded Ti components should be addressed to improve RSW procedures and increase the reliability of welded Ti components.

This review presents the advances in RSW of Ti and its alloys, focusing on the most recent research, techniques and technological innovations that improve welding outcomes. The novelty of this review lies in the detailed study of developments in RSW with respect to Ti and its alloys. Although RSW is a widely used technology in many industries, the characteristics and important applications of Ti and its alloys create special opportunities and problems for its implementation. Previous papers have covered RSW in general or focused on other materials. This review focuses on the behavior of Ti and its alloys during RSW, which has remained unexplored despite the increasing importance of these materials. Although process parameters in RSW may have been covered in some earlier works, this review highlights that factors such as sheet thickness, welding current, welding time, electrode force, electrode diameter and tensile loading impact the weld quality in Ti and its alloy. This present observations not commonly found in existing literature. The research gaps in the influence of electrode diameter, material thickness, and behavior of specific Ti alloys such as AMS 4902 are addressed, and these are less commonly studied in RSW applications. Finally, future research directions are proposed, including optimising RSW techniques for thicker Ti sheets and studying electrode wear and behavior under different operational conditions to improve the RSW quality and performance in industrial applications. This review provides a new perspective by integrating the most recent studies and technological developments in RSW for Ti and its alloys. Also, this review provides a critical analysis that would be a valuable resource for researchers and practitioners seeking to improve welding outcomes for these advanced materials. The study's objectives are as follows;

- To examine and synthesize existing literature on the techniques, processes, and outcomes of RSW in Ti and its various alloys.
- To investigate the effects of various process variables on the quality of the weld in titanium and its alloys, including sheet

thickness, welding current, welding time, electrode force, electrode diameter, and tensile loading.

- To analyze challenges and limitations associated with the RSW of Ti and its alloys
- To provide recommendations for further investigation and suggest improvements in RSW practices to enhance weld quality and efficiency.

The structure of the paper is organized into the following sections: Section 2 provides a comprehensive overview of RSW, including its principles and fundamentals and its application in welding Ti and its alloys. Section 3 focuses on commonly used Ti alloys in RSW and the impact of alloy composition on the welding process and weld quality. It also discusses surface preparation and nugget formation of Ti alloys in RSW. Section 4 explains how several process variables affect the quality of the welds in RSW, especially when utilizing titanium and its alloys. Section 5 summarizes the important findings from existing research on the RSW of Ti and its alloys and identifies any gaps or topics for future study. Section 6 summarizes and addresses probable future research areas in RSW with Ti and its alloys.

2. Resistance Spot Welding (RSW)

2.1. Principles and Fundamentals of RSW

Resistance spot welding joins metal sheets using heat generated by an electric current passing through metal sheets. The process is based on Joule's law, which explains the heat Generation (Q) as a function of the square of the current (I), Resistance (R), and Time (t), as expressed in Equation (1).

$$Q = I^2Rt \tag{1}$$

The RSW procedure concentrates the welding current on a tiny region, clamping the sheets to ensure perfect alignment, using alloy electrodes shaped like cones or domes. The sheets are held under the pressure of the electrodes and generally range from 0.5 to 3 mm in thickness. The high current causes limited melting at the spot, which forms a weld. Energy distribution in RSW is 10 to 100 milliseconds, confirming that the surrounding material is not overheated. The amount of heat energy transferred to the weld spot is determined by the magnitude and duration of the welding current, along with the interface's resistance. The workpiece's characteristics, including its electrical conductivity, thermal conductivity, and thermal expansion, are used to calibrate the energy. Insufficient energy results in poor weld strength, while excess energy can lead to excessive melting and voids in the weld [11].

Figure 1 depicts a schematic representation of the RSW process.RSW involves three main stages: (a) bringing the electrodes into contact with the metal sheets and applying light pressure, (b) applying the welding current for a brief duration, and then removing the current while maintaining the electrode pressure for cooling and solidifying the weld. The weld duration typically ranges from 0.01 to 0.8 seconds, depending on factors such as electrode force, thickness, and electrode tip diameter of the metal. Alloy electrodes and tool holders are components of the RSW system. In addition to supporting the cooling water hoses that control electrode temperature, the tool holds the electrodes. Light-duty paddle-type, universal, and offset arrangements are common ways to carry tools. Typically composed of copper, electrodes can have a flat, dome, or truncated cone shape depending on the application [13].

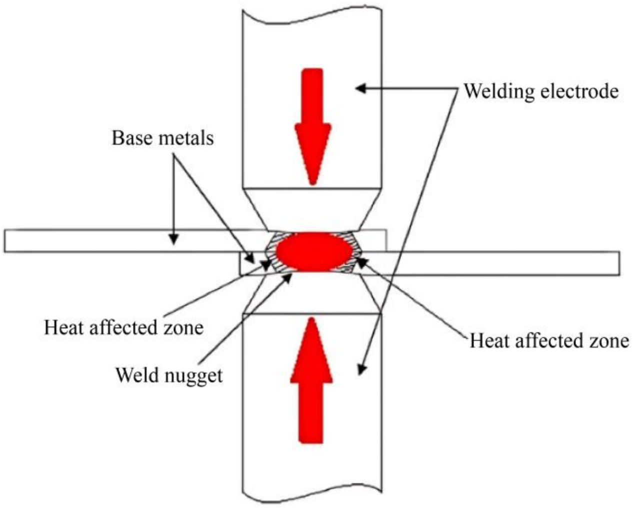

Fig. 1 Representation diagram of RSW [12]

The workpieces, the welded metal sheets, should be effective electrical conductors. The throat length of the welding apparatus, which ranges from 13 to 130 cm (5 to 50 inches), forces the width of the metal sheets, and the thickness varies from 0.2 to 3 mm. In RSW, the tooling system includes two essential elements affecting the process: (a) the welding gun and (b) electrode size and shape. The C-type gun provides stiffness and tooling versatility, making it suitable for high-force applications. On the other hand, the X-type gun provides a larger working area but less rigidity. The selection of electrodes is based on their purpose. Radial electrodes are employed in high-temperature applications, and truncated tips are used in high-pressure applications. To facilitate corner welding, offset truncated tips for the workpiece and offset eccentric tips for difficult-to-reach places are designed into eccentric electrodes [14].

The RSW process can induce work hardening due to electrode force application, potentially causing warping. This results in stretching or annealing and lowers the material's fatigue strength. Poor appearance, liquation cracking within the weld nugget, and internal cracking are common spot welding faults. Additionally, there are modifications to chemical characteristics, such as greater sensitivity to corrosion and changed internal resistance. Short welding times can lead to electrode wear, as the electrodes do not move quickly enough to maintain a consistent clamp. During initial pulses, electrode contact does not create a robust weld, softening the metal. The interval between pulses allows the electrodes to approach the workpieces more closely, which enhances contact quality. High welding currents create substantial magnetic fields, generating magnetic forces that can accelerate molten metal up to 0.5 m/s. This rapid metal movement can alter heat distribution within the spot weld. High-speed cameras can capture the swift motion during spot welding.

A basic RSW setup consists of a power source, switch, energy storage (capacitor bank), welding transformer, and electrodes. The welding transformer receives instantaneous high power from the capacitor bank. The transformer mostly modifies the voltage load on the switch by decreasing the voltage while raising the current. The welding electrodes are located in the transformer's secondary circuit, and a control box controls the switch and keeps watching the electrode voltage or current. Multiple resistances within the system contribute to the complexity of the process. This includes resistance from cables, secondary windings, electrodes, and contact resistance between the electrodes and workpieces. Initially, high contact resistances result in energy loss. However, applying clamping force helps make the material at the interface between the electrode and material smoother and softer. This improves the quality of the contact and reduces resistance. As a result, the workpiece receives more electrical energy, which increases the resistance between the workpieces. Rising temperatures and heat dissipation through the workpieces and electrodes impact the weld. Achieving the correct energy balance ensures a targeted melt without oversaturating the spot.

Because of thermal conductivity, heat diffuses from the spot's edge, maintaining a lower temperature in the surrounding area. As a result, the spot's core melts first; the necessary working voltage for welding is determined by the thickness of the sheet, the resistance of the workpiece, and the size of the desired weld nugget. The voltage between the electrodes for a 2 mm lapped joint begins at approximately 1.5 V. It may decrease to 1 V by the end of the weld, indicating the workpiece melting-related decrease in resistance. The transformer's open-circuit voltage varies from 5 to 22 V and is often higher [15]. Since RSW is becoming important, there is a need to focus on RSW's environmental impact and safety. The process can produce emissions of fumes and gases released during welding. This requires proper ventilation and air filtration systems to maintain worker health. Additionally, RSW needs energy input, which is increasing concerns about energy consumption and its implications for sustainability. Applying energy-efficient practices and technologies supports lessening these impacts. Workplace safety is important; safety procedures should be followed to protect operators from hazards associated with heat generation, high currents and potential electrical risks. Safeguarding proper training and equipment maintenance further improves the safety of the RSW process.

2.2. Applications of RSW

Resistance spot welding is a popular method of attaching thick steel plates, offering an alternative to traditional methods such as riveting. Spot welding is a cost-effective method of connecting several sheet metal components without gas-tight sealing. This method is suitable for fastening pads, braces, and clips to sheet metal parts. Table 1 shows the applications of RSW in various alloy types.

Table 1. Applications of RSW in various alloy types across different industries

Alloy type	Industry	Applications	References
Low Carbon Steel	Automotive	❖ Body Panels ❖ Chassis Components ❖ Doors and Hoods ❖ Exhaust Systems	[16-19]
	Appliance	❖ Microwave Cabinets ❖ Refrigerator Shells ❖ Washer and Dryer Panels	
	Electronics	❖ Battery Packs ❖ Metal Enclosures	
	Construction	❖ Fabrication of Metal Structures	
High Strength Steel	Automotive	❖ Structural Components (e.g., A-Pillars, B-Pillars) ❖ Crash Zones	[1, 20, 21]
	Aerospace	❖ Aircraft Structural Components ❖ Engine Casings	
	Construction	❖ Heavy Structural Applications	
Stainless Steel	Automotive	❖ Fuel Tanks ❖ Exhaust Systems	[22, 23]

	Appliance	❖ Cutlery ❖ Kitchen Appliances ❖ Sinks and Countertops	
	Food Processing	❖ Brewing and Distilling Tanks ❖ Equipment and Containers	
	Construction	❖ Metal Structures	
Aluminum alloys	Automotive	❖ Wheels ❖ Body Panels	[24, 25]
	Aerospace	❖ Aircraft Skins ❖ Fuel Tanks ❖ Structural Components	
	Electronics	❖ Heat Sinks ❖ Battery Enclosures	
	Construction	❖ Lightweight Metal Structures	
Copper and alloys	Electrical	❖ Wiring Terminals ❖ Transformer Components ❖ Electrical Contacts ❖ Bus Bars	[26]
	Construction	❖ High Conductivity Parts for Electrical Systems	
Nickel alloys	Aerospace	❖ Gas Turbine Components ❖ Jet Engine Components	[27]
	Oil & Gas	❖ Valves and Fittings ❖ High-Temperature and Corrosion-Resistant Piping	
	Medical	❖ Orthopaedic Implants	
Titanium alloys	Aerospace	❖ Engine Components ❖ Aircraft Structural Components	[28, 29]
	Medical	❖ Medical Implants	
		❖ Surgical Instruments	
Magnesium alloys	Automotive	❖ Steering Wheels ❖ Instrument Panels ❖ Transmission Cases ❖ Brake Components	[30, 31]
	Aerospace	❖ Aircraft Interior Components	
		❖ Structural Components	
	Consumer goods	❖ Laptop Cases	
		❖ Mobile Phone Bodies	
	Electronics	❖ Camera Casings	
		❖ Heat Sinks	
	Heating, Ventilation, and Air Conditioning (HVAC)	❖ Ducting and Piping	
	Construction	❖ Lightweight Metal Structures	
Other applications	Other	❖ Orthodontic Practices for Adjusting Metal Bands ❖ Connecting Metal Straps to Battery Cells in Devices ❖ Production of Household Appliances ❖ Metal Furniture Fabrication ❖ Creation of Industrial Equipment and Machinery ❖ Shipbuilding and Marine Industry Applications ❖ Custom Metal Fabrication ❖ Clean and Contamination-Free Surfaces for Quality Welds	[32, 33]

2.3. Challenges

Because resistance spot welding is quick, easy, and inexpensive, it is a common method for connecting metal sheets in various industries. However, RSM comes with its challenges in the manufacturing process. Here are some key challenges associated with RSM: Regular maintenance and dressing of electrodes are needed to ensure consistent welding quality. Electrodes in RSW are subject to wear and tear, leading to shape and electrical resistance changes over time. Excessive wear can result in poor weld quality and increased electrode replacement downtime, as Panza et al. noted [10]. Zhao et al. [34] and Dai et al. [35] have demonstrated that poor-quality welds can result from inadequate clamping force, inconsistent current, or improper welding parameters. Achieving consistent weld quality is challenging due to variations in sheet thickness, material properties, and surface conditions. Kumar et al. [36] explain that welding dissimilar metals or coated metals requires specific welding conditions or adjustments to parameters, as well as different metals possess varying electrical and thermal properties, which can affect the RSW process. Zhang et al. [37] highlighted that high heat concentration can lead to damage, distortion, or warping of the workpieces. Managing heat dissipation during welding is important to avoid overheating the surrounding material. Advanced control systems and sensors are needed to maintain consistent welding conditions. High welding currents create substantial magnetic fields, leading to magnetic forces that disrupt the weld and affect its quality. Proper handling of these forces is necessary to maintain consistent weld nugget formation. Das et al. [38] discovered that adjustments to welding parameters are needed to accommodate these variations, such as surface coatings, workpiece thickness, or flatness, which can affect the welding process and weld quality. The integrity of the workpiece and the weld's strength and longevity can be impacted by the pressure the electrodes apply. The initial cost of RSW equipment, including welding machines and electrodes, can be significant. Maintenance and replacement costs for electrodes and other consumables add to the overall expense. The RSW process generates heat and sparks, which can pose safety hazards in the workplace, as demonstrated by Riccelli et al. [39]. Therefore, proper ventilation and safety measures are needed to protect workers and equipment.

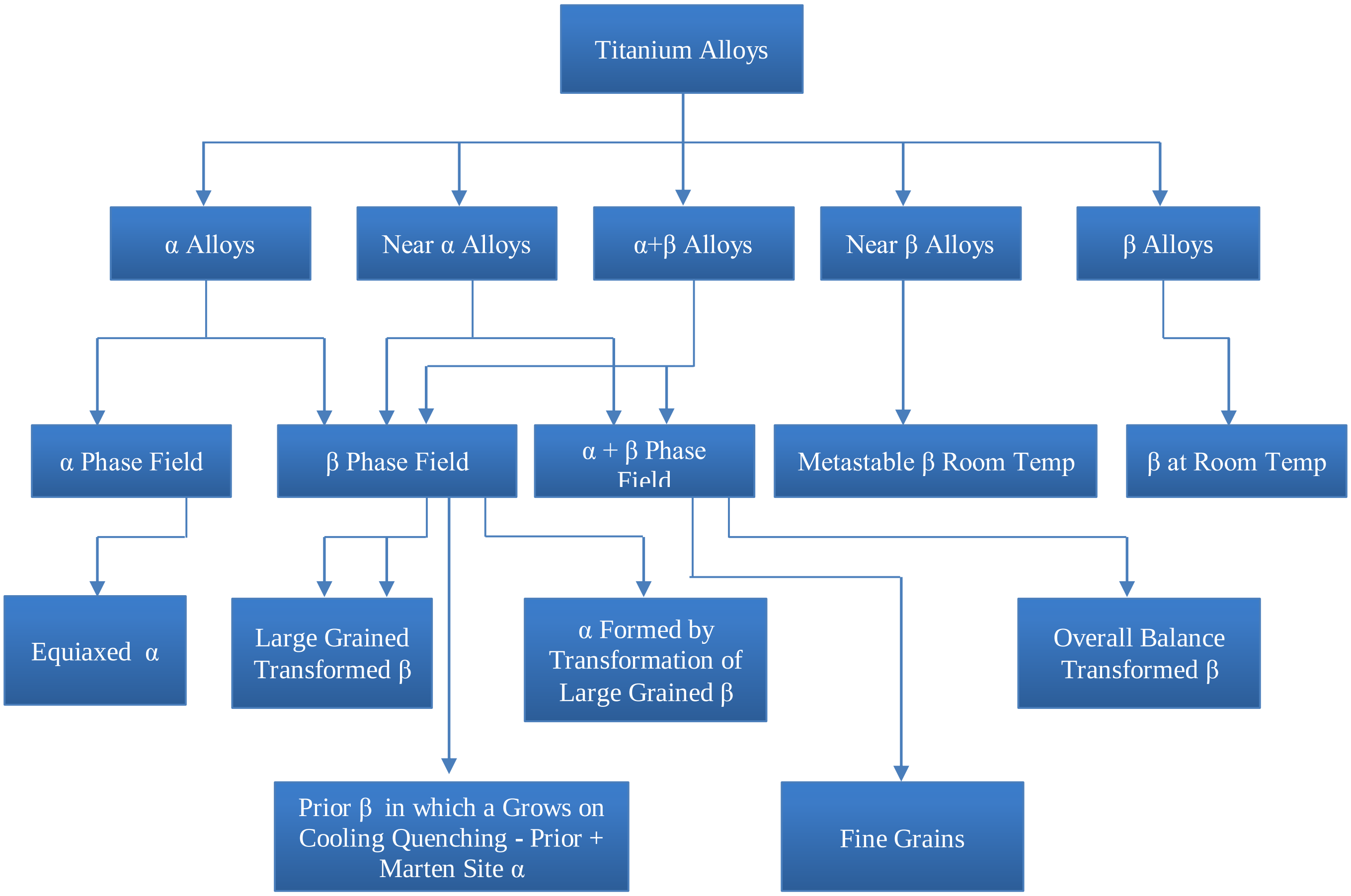

Fig. 2 Various types of Ti alloy [41]

3. Titanium Alloys

The adaptable metal titanium is renowned for its exceptional resistance to corrosion, high strength-to-weight ratio, and biocompatibility. Titanium is a chemical element on the periodic chart. It has an atomic number of 22 and is represented by the symbol Ti [40]. This metal is classified as a transition metal due to its exceptional strength, relatively low density, and silver color. Titanium ranks as the ninth most abundant element in the Earth's crust when considering its pure forms. Alternatively, it can be found in minerals like rutile, sphene, and ilmenite. The Kroll procedure reduces Titanium Tetrachloride ($TiCl_4$) with magnesium or sodium to create titanium. The Hunter procedure, which includes reducing TiCl4 with hydrogen, is a further technique. By mixing Ti with other metals like vanadium, aluminum, iron, or nickel, titanium alloys are produced. Figure 2 shows the various Ti alloy categories and the influence of hot working on microstructure [41]. In recent years, advanced welding technologies such as friction stir welding, laser welding, electron beam welding, and arc welding have significantly increased consideration for their advantages in joining Ti and its alloys. Laser welding provides high precision and control over heat input, which results in reduced weld defect risk and diminished thermal distortion. Friction stir welding is a solid-state process, and it is known for developing high-strength joints without melting base materials, which is suitable for thick sections. Electron beam welding permits deep penetration and high welding speeds in a vacuum, making it suitable for aerospace applications. Ti is welded using Gas Tungsten Arc Welding (GTAW) because it produces high-quality welds. By using these advanced welding methods, manufacturers can overcome challenges caused by the RSW of Ti. It confirms improved welded parts' performance and integrity in industrial, medical and aerospace applications.

Table 2. Various types of Ti alloys and their properties [42]

Category	**Chemical Composition (% of Weight)**	**Hardness (HV)**	**Yield Strength (MPa)**	**Tensile Strength (MPa)**	**Elastic Modulus (GPa)**	**T_β (˚C)**
α						
High purity Ti	99.98 Ti	100	140	235	100-145	882
Alloy grade 6	Ti-5Al-2.5Sn	300	827	861	109	1040
CP-Ti grade 4	0.5Fe-0.40O	260	480-655	>550	100-120	950
CP-Ti grade 1	0.2Fe-0.18O	120	170-310	>240	-	890
Near-α						
TIMTETAL 685	Ti-6Al-5Zr-0.5Mo-0.25Si	-	850-910	990-1020	120	1020
Ti-6-2-4-2-S	Ti-6Al-2Sn-4Zr-2Mo-0.1Si	340	990	1010	114	995
TIMETAL 1100	Ti-6Al-2.7Sn-4Zr-0.4Mo-0.4Si	-	900-950	1010-1050	112	1010
α+β						
Ti-17	Ti-5Al-2Sn-2Zr-4Mo-4Cr	400	1050	1100-1250	112	890
Ti-6-2-4-6	Ti-6Al-2Sn-4Zr-6Mo	300-400	1000-1100	1100-1200	114	940
Ti-6-6-2	Ti-6Al-6V-2Sn	300-400	950-1050	1000-1100	110-117	945
Ti-6-4	Ti-6Al-4V	300-400	800-1100	900-1200	110-140	995
Near-β						
Ti-10-2-3	Ti-10V-2Fe-3Al	300-470	1000-1200	1000-1400	110	800
Beta III	Ti-11.5Mo-6Zr-4.5Sn	250-450	800-1200	900-1300	83-103	760
Ti-15-3	Ti-15V-3Cr-3Al-3Sn	300-450	800-1000	800-1100	80-100	760
Beta C	Ti-3Al-8V-6Cr-4Mo-4Zr	300-450	800-1200	900-1300	86-115	795
SP 700	Ti-4.5Al-3V-2Mo-2Fe	300-500	900	960	110	900

T_β –Beta transus temperature

These Ti alloys enhance properties such as strength, corrosion resistance, or heat resistance. Titanium's robustness and corrosion resistance make it advantageous for military purposes, including armor plating and missile components. Titanium and its alloys are extensively utilized in aircraft applications because of their exceptional strength-to-weight ratio. The study was conducted on aircraft structures, engine components, and spacecraft. Ti's biocompatibility makes it suitable for medical implants such as orthopaedic implants, dental implants, and surgical instruments. Titanium alloys are used in a wide range of industrial applications, such as sporting products, chemical processing equipment, and naval components. Despite being exposed to severe environments like seawater and chemical solutions, titanium has strong corrosion resistance. The distinctive mechanical properties and compositions of various Ti alloys are important factors in selecting the most suitable for specified applications. For example, alpha alloys have improved creep resistance at high temperatures than alpha-beta alloys. It is important to understand these differences in order to improve performance in several industrial sectors. Titanium alloys have high tensile strength, comparable to many steels, but with lower density. Titanium is about 40% lighter than steel and is suitable for weight-sensitive applications. Titanium is non-toxic and biocompatible and is used for medical implants without risk of adverse reactions [41, 42]. Table 2 shows the types of Ti alloys and their properties.

3.1. Impact of Ti Alloy Composition on RSW Welding Process and Weld Quality

The remarkable durability and resistance to corrosion of titanium make it highly beneficial for military applications, such as the production of armor plates and missile components. Titanium and its alloys are widely used in aircraft applications because of their outstanding strength-to-weight ratio. However, it is necessary to distinguish the effects of welding parameters on different Ti alloys because of their different compositions and mechanical properties. Process parameters were shown to significantly impact joint strength and failure mode, with optimal circumstances yielding the highest strength. Weld nugget size, hardness and failure mode can vary between alpha alloys, which require lower heat inputs during welding and alpha+beta and near beta alloys, which might be more sensitive to parameter variations. Fatmahardi et al. [12] focused on the RSW of Ti-6Al-4V, concentrating on the mechanical characteristics and weld quality. Using the Taguchi L9 method, the study identified optimal welding parameters for joint strength. High heat input increases weld nugget diameter and hardness but decreases ductility due to martensite microstructure formation. Expulsion occurs under high heat input, which reduces weld nugget strength. The study highlighted the importance of controlling welding parameters for desired mechanical properties. For example, in alpha+beta alloy Ti-6Al-4V, the weld quality is very sensitive to heat input and cooling rates and can change the joint’s microstructure and mechanical properties. The effect of Electromagnetic Stirring (EMS) on Al/Ti resistance spot welds was examined by Li et al. [43]. The microstructures of Al/Ti and Al/Al welds were studied, and the impact of welding settings on tensile shear characteristics was investigated. Greater energy absorption, larger bonding diameter, and higher tensile shear stress are all results of EMS’s finer spheroidal grain structure compared to traditional welding. Al/Ti EMS joints exhibited superior mechanical performance, which was attributed to their improved bonding diameter and finer grain structure. Using an aluminium interlayer, Taufiqurrahman et al. [44] investigated the microstructure and mechanical characteristics of different spot welds between SS316L and Ti6Al4V. The optimal requirements yield a maximum hardness of 367.3 HV and a tensile-shear load of 895 N. Holding time influences void formation within the weld nugget, with increased holding time enhancing weld strength by eliminating voids. Bozkurt and Çakır [45] combined experimental and numerical approaches to analyze Ti6Al4V spot welds. Taguchi L9 orthogonal design identified optimal welding parameters, which were validated experimentally.

Numerical modeling with the Finite Element Method (FEM) aids in understanding weld strength and unpredictability. Parameter optimization enhances joint quality and validates the numerical model. Utilizing aluminum interlayer in SS316L/Ti6Al4V RSW, Taufiqurrahman et al. [46] optimized welding parameters for joint strength. Optimal parameters result in a tensile-shear load of 8.83 kN, with different interface morphologies and intermetallic compound formation. The study highlighted the importance of parameter optimization for achieving desired mechanical properties. Ti6Al4V is highly sensitive to microstructural changes during welding, and weld quality is highly dependent on precise control of heat input and electrode force.

Butsykin et al. [47] investigated preheating and slow cooling effects on Ti-2Al-1Mn resistance spot welds. Optimal energy parameters reduced nugget diameter dispersion and enhanced fracture energy and peak load. Preheating and slow cooling stages further improved joint stability and mechanical properties, attributed to reduced residual stresses. Examining RSW of grade 2 Ti alloy, Mezher et al. [29] evaluated welding parameters’ effects on micro-hardness, shear force, and failure mode. Experimental results and ANN modeling demonstrated parameter influence on mechanical properties, with optimal conditions yielding improved joint strength and hardness. Different failure modes were observed, highlighting the need for precise parameter control. Therefore, the welding parameters must be matched to suitable alloy composition for proper welding between different Ti alloy grades to achieve optimum joint quality.

Moreover, considering the economic aspects of RSW for Ti alloys is necessary for industrial feasibility. A comprehensive cost-benefit analysis must include equipment investments, operational costs and potential savings from superior durability and shortened maintenance requirements. Evaluating the economic impact of RSW can provide an understanding of its practicality in sectors where Ti alloys are important, such as aerospace and defense. This would help manufacturers understand how to adopt RSW technologies for Ti applications based on these economic factors. Table 3 summarizes the impact of Ti alloy composition on RSW.

Table 3. Summary of the impact of Ti alloy composition on RSW

Study	Materials	Welding Process	Methods	Findings
Bozkurt et al. [9]	Ti6Al4V	RSW	Taguchi L9 method, variance analysis, characterization	The welding settings affected the manner of failure and the strength of the joint; the ideal parameters produced the strongest joints under static and dynamic circumstances.
Fatmahardi et al. [12]	Ti-6Al-4V	RSW	Taguchi L9 method, microstructure analysis, hardness	High heat input led to increased weld nugget diameter, expulsion, martensite microstructure, increased hardness, and strength, but decreased ductility.

Li et al. [43]	Al/Ti	RSW	Microstructure characterization, tensile shear properties	EMS resulted in finer spheroidal grain structure, higher tensile shear force, larger bonding diameter, and energy absorption compared to traditional welding.
Taufiqurrahman et al. [44]	SS316L/Ti6Al4V	RSW	Tensile-shear test, microstructure analysis	Aluminum interlayer improved weld quality, holding time reduced voids in weld nugget, and increased tensile-shear load.
Bozkurt and Çakır [45]	Ti6Al4V	RSW	Numerical modeling, Taguchi L9 method, ANOVA	Optimizing the weld parameters electrode force, welding time, and welding current greatly enhanced the strength of the resulting joint.
Taufiqurrahman et al. [46]	SS316L/Ti6Al4V	RSW	Taguchi method, mechanical structure analysis, EDX	Optimized parameters produced a high tensile-shear load; the aluminum interlayer formed intermetallic compound layers, which improved joint strength.
Butsykin et al. [47]	Ti-2%Al-1%Mn alloy	RSW	Experimental evaluation, preheating, slow cooling	As a result of decreased residual stresses, fracture energy and peak load were enhanced during the preheating and slow cooling phases, which also decreased the dispersion of nugget sizes.
Mezher et al. [29]	Titanium sheets	RSW	Design of experiments, ANN models	Welding parameters affected shear force and hardness; the 0.5-0.5 mm case showed the highest hardness, and ANN predicted optimal parameters effectively.

3.2. Surface Preparation of Ti Alloys

Titanium alloys are prepared for RSW through various surface treatments aimed at ensuring proper weld quality and preventing issues such as contamination and poor electrode contact. Common methods for surface preparation of Ti alloys include chemical cleaning, which removes surface contaminants and oxides from Ti alloys. Acid-based solutions such as a mixture of sulfuric acid and hydrofluoric acid are commonly used for this purpose. The chemical cleaning process helps to improve the uniformity of contact resistance and facilitates better weld quality [48, 49].

Additionally, surface preparation methods affect the mechanical properties of welded joints. Improper cleaning can lead to defects such as cracks and porosity which adjusts the integrity of the weld. Therefore, a systematic approach to optimizing these surface preparation techniques is important to increase the overall performance of RSW in Ti alloys.

In the surface preparation for RSW of Ti alloys, Ghalib et al. [50] explored the efficacy of chemical cleaning as a method. Using a tiny amount of Ti powder between the faying surfaces, the article reveals a new method for increasing corrosion resistance during spot welding. Researchers looked at how a spot-welded alloy behaved when immersed in a solution of one molar sulfuric acid in water. Microstructural alterations were observed during the spot welding process. Mechanical abrasion techniques such as sanding or grit blasting remove surface impurities and oxides from Ti alloy surfaces [51].

Yu et al. [52] state that abrasion helps to create a clean and roughened surface, which promotes better adhesion and penetration during the RSW process. Inert gases like argon or helium are used to insulate surfaces of Ti alloys from air contamination. By acting as a barrier, this shielding keeps surfaces free of oxidation and makes welding much easier [53].

Grain structure and phase transformation characteristics of welded Ti alloy are essential to be understood. Mechanical properties and performance of welded joints depend on these aspects in the case of varying welding conditions. In addition, the joint formation of intermetallic compounds during the welding process also affects the joint durability and reliability of joints. Figure 3 demonstrates the microstructural analysis of a Ti-6Al-4V alpha-beta Ti alloy [54]. Proper surface preparation is essential for achieving high-quality welds when using RSW of Ti alloys. It helps to minimize variations in contact resistance, reduce electrode fouling, and ensure optimal weld performance.

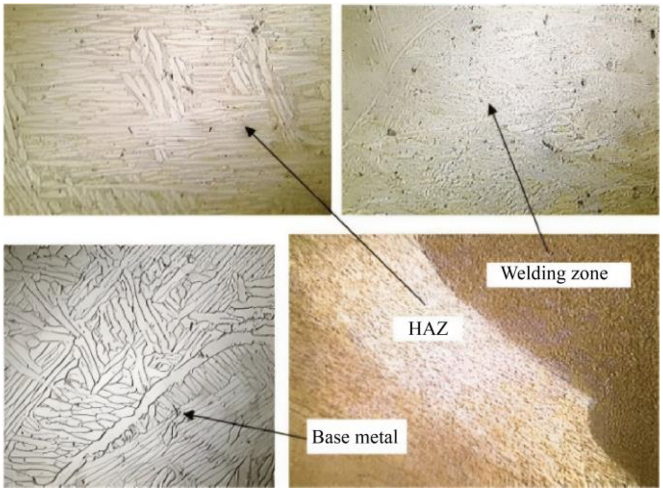

Fig. 3 The microstructure of a Ti-6Al-4V alpha-beta Ti alloy after the welding process [54]

3.3. Nugget Formation of Ti Alloys

Ti alloys' nugget formation process during RSW has a pattern comparable to other metallic materials. In the initial stage of nugget formation, known as the incubation stage, the Ti alloy begins to melt due to the heat applied to it by the welding current. This stage is relatively short and typically lasts less than one welding cycle. During this phase, the nugget forms as the material softens and fuses [55]. Following the incubation stage, the nugget enters the growth stage, lasting approximately 2 to 4 welding cycles. The nugget grows rapidly in this stage as more material is melted and fused together [56]. The growth rate decreases with time due to a drop in current density and heating rate when the contact area between the electrode and workpiece increases. Welding achieves a stable state, and nugget growth stabilizes after about four rounds. At this point, the size and shape of the nugget remain relatively constant, indicating that the welding parameters are well-balanced and the desired weld quality has been achieved. Understanding the stages of nugget formation in Ti alloy RSW is crucial for optimizing welding parameters and ensuring consistent and reliable welds. Proper control of welding parameters, including current, time, and pressure, is essential for achieving desirable nugget characteristics and overall weld quality.

Kumar et al. [57] compared the mechanical and microstructural characteristics of Ti-6Al-4V alloy that was spot-welded. Weld duration cycles of 30, 50, and 70 were employed to join thin sheets (750 μm) of Ti-6Al-4V alloy using RSW. During Post-Weld Heat Treatment (PWHT), the weld pad was heated to around 915°C, which is the β-transus temperature, for a duration of 60 minutes. Subsequently, it was quenched with water in order to reduce its temperature. Improving the weld time led to enhanced mechanical properties with 70 cycles, which was determined as the optimal duration for welding. The solution treatment improved the tensile-shear load-bearing capacity and extension by converting the interfacial failure mode to pullout. Ertan [58] looked into the mechanical characteristics of different Ti-Al resistance spot welds. Using RSW, titanium alloy sheets (ASTM Grade 2) and 5754 aluminum alloy were welded together. Various welding parameters were utilized, including electrode pressures ranging from 5 to 15 kN, welding currents of 10, 12, and 15 kA, and cycles of 10, 15, and 20. The research looked at the weld nugget's dimensions, including its diameter and height, and the outcomes of hardness and tensile-shear tests. The welding parameters had a significant influence on the mechanical properties of the joints. Increasing the welding current and duration enhanced the tensile-shear load but lowered the electrode force. Using Ti-1Al-1Mn thin foils as an example, Chen et al. [59] investigated the effect of welding conditions on the RSW at a small scale. Key welding parameters such as holding time, ramp time, welding current, welding time, and electrode force were the primary focus of the investigation. An analysis was conducted to assess the weld shape, microstructure, microhardness, and element distribution. The surface indentation reached a stable diameter of around 365 μm and a thickness of about 8 μm. The weld nugget exhibited the maximum microhardness value, while the HAZ showed softening. Weld nugget size, failure mode, and average HAZ grain size were the three factors that ultimately decided the welded joint's maximum load-bearing capacity. The spot welding parameters employed, such as a 12-cycle welding time, 9 kA welding current, and 3 kN electrode force for the Ti6Al4V Ti alloy, are shown in Figure 4, a cross-sectional view of the joint. Despite the alloy sheet's thinness (1 mm), high welding heat achieves the desired weld width, leading to full melting from the faying surfaces outward. The differing material properties (Ti_6Al_4V alloy sheet and Cu-Cr alloy electrodes) make adhesion challenging, but no significant contamination or damage occurs. The joint consists of a weld nugget, HAZ, and base metal, each with clearly defined limits. The strength of a joint is influenced by the morphology of the weld, which may be assessed by measuring the width of the weld nugget (W) and the height of the joint (H), as depicted in Figure 4 [60].

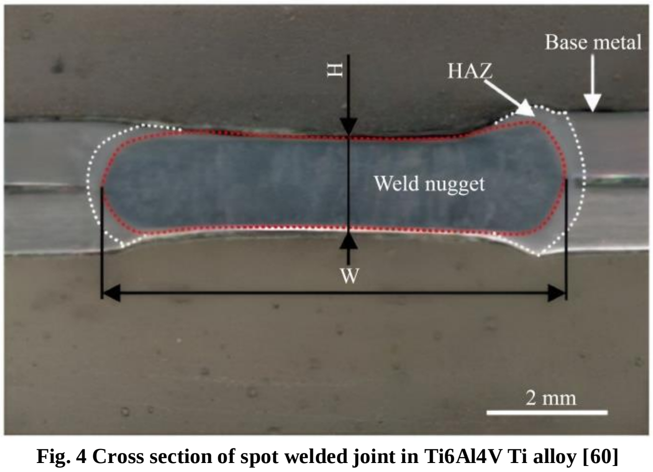

Fig. 4 Cross section of spot welded joint in Ti6Al4V Ti alloy [60]

4. Influence of RSW Process Parameters on Weld Quality

An investigation on the influence of welding current and electrode force on the quality of SS316L/Ti6Al4V with an aluminum interlayer was carried out by Taufiqurrahman et al. [61]. The weld current varied between 11 and 13 kA, while the electrode force ranged from 3 to 5 kN. Both welding and holding periods were constant. Increased current and force led to higher heat input, and the highest tensile-shear load, 8.71 kN, occurred with 11 kA current and 3 kN force. High-current welding produced brittle fractures and defects. Microstructural analysis showed grain growth in SS316L and phase transformation in Ti6Al4V. Intermetallic compound layers were examined using EDX and XRD, which revealed different fusion zones with high microhardness values for both metals. Stainless steel 316L and Ti-6Al-4V were welded by Mansor et al. [62] using micro-RSW, varying welding parameters, and electrode geometry. Tensile shear tests determined joint strength, while microstructural analysis examined fracture modes. Welding conditions that produced the best results were a current of 2.0 kN, duration of 100 ms, and force of 241 N, for a total load of 378.25 N.

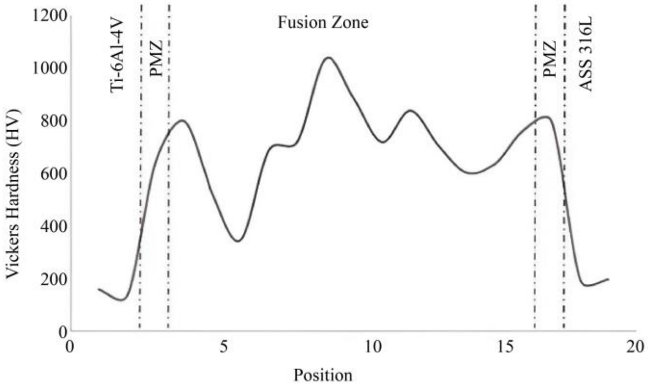

Fig. 5 Microhardness profile of RSW joint at 1.8 kA, 150 ms, and 362 N [62]

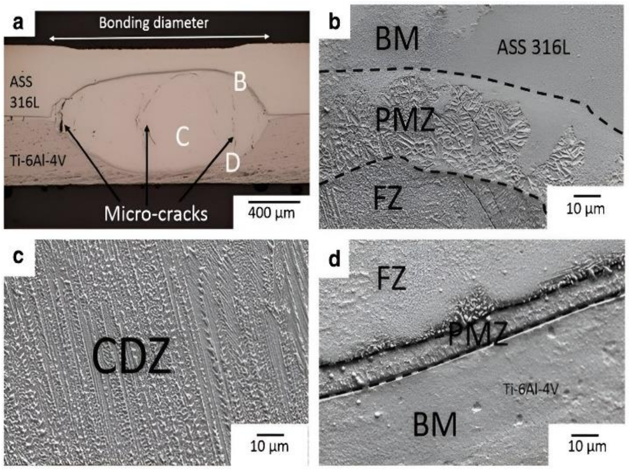

Fig. 6 The big and small structures of the RSW combined areas A, B, C, and D [62]

The results were shown to be significantly affected by the welding current. However, in order to avoid the discharge of weld metal, control was required. SEM and EDS mapping revealed columnar dendritic structures at the fusion zone. Figure 5 displays the Vickers micro-hardness profile of the RSW joint, where the welding parameters were adjusted to a weld time of 150 milliseconds, weld current of 1.8 kiloamperes and weld force of 362 Newtons. Figure 6 illustrates the macrostructure and microstructure of various regions (A-D) in a microresistance spot welded joint. The pictures showed how ASS 316L and Ti-6Al-4V successfully fused, solidifying into a nugget since the welding temperature was higher than their melting temperatures.

Investigating the connection between dynamic resistance and RSW quality estimation was the focus of Zhao et al. [63]. Twenty characteristics were extracted from the welding process's dynamic resistance signal. The test made use of TC2 Ti alloy specimens. A 3 mm electrode tip width was used in conjunction with a welding current ranging from 1.0 to 2.4 kA, a welding period from 4 to 12 ms, and an electrode force ranging from 76.2 to 203.2 N. According to the results, the welding current significantly affected most of the measured features. The model was very good at predicting welding quality, with a maximum relative error of less than 10%. To forecast the TC2 Ti alloy welding quality, Zhao et al. [34] used regression and NN models to examine the impacts of welding variables and changes in dynamic resistance curves. Principal Component Analysis (PCA) eliminated redundant information and characterized curve shape, enhancing regression model robustness. Results highlighted PCA reliability in assessing and monitoring welding quality, indicating its superiority over manual feature extraction methods. When it came to Resistance Element Welding (REW), Wang et al. [64] investigated 7075 aluminum alloy to Ti6Al4V Ti alloy. The study created a metallurgical connection by inserting Ti6Al4V rivets into holes in an aluminum sheet and then resistance welding the components. The study examined the joints' hardness distribution, microstructure, mechanical properties, and fracture mode. The findings showed that compared to riveted connections, REW joints were better at absorbing energy and withstanding tensile shear loads, with both metrics improving as the rivet diameter grew larger.

As the welding current increases, different failure modes are experienced. The nugget's microstructure is mostly made up of acicular α′ phase martensite, and at the Ti/Al interface, a layer of discontinuous intermetallic compounds is formed. In order to forecast the nugget diameter of spot-welded joints, Zhao et al. [65] monitored the dynamic power signature. The study compared the efficacy of a regression model with that of an Artificial Neural Network (ANN).

High-frequency precision spot welder settings for joining TC2 Ti alloy sheets (100x30x0.4mm) included a welding duration of 4 to 12 ms, a welding current of -1.0 to 2.4 kA, and an electrode force of 76.2 to 203.2 N, with increments of 0.2, 2, and 25.4 N, respectively. The Rogowski coil captured dynamic welding current while electrodes detected voltage. Five power signal characteristics described curve shapes, aiding in classifying welds as bad, good, or with expulsion. Through dynamic power signature monitoring, Zhao et al. [66] explored real-time nugget size prediction in TC2 Ti alloy welding joints. Welding current and voltage were recorded similarly with features extracted from power waveforms for quality prediction via the Kriging method. Experimentally verified and Kriging method enabled effective monitoring and assessment of RSW processes under constant current and voltage modes. Scatter graphs illustrating the correlation between ΔP_1 and nugget diameter, P_S and nugget diameter, and Q and nugget diameter are presented in Figure 7 [66].

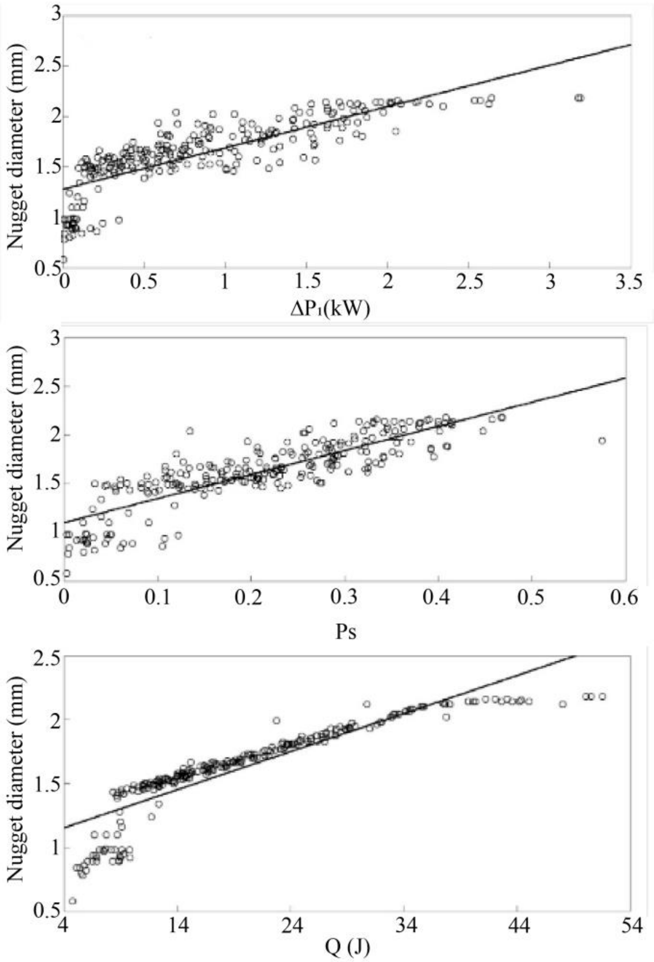

Fig. 7 Nugget diameter plotted against ΔP_1, P_S, and Q [66]

Liu et al. [67] looked at the RSW of the dissimilar alloys TA15 Ti and AZ31 Mg and the effect of welding current on nugget contacts. The study examined hardness, microstructure, tensile strength, and fracture surface by varying electrode pressure, welding current, and welding time. Optimal conditions achieved a failure load of 4.79 kN, similar to AZ31B magnesium alloy shear strength. Even though excessive welding current leads to interface cracks, demonstrated at 200 ms welding time and 14 kA with 0.22 MPa pressure, incomplete melting formed a ‘fish scale’ microstructure near the magnesium alloy interface, causing fracture. In order to optimize RSW parameters on TC2 Ti alloy sheets for several objectives, Zhao et al. [68] suggested a hybrid method that combines regression analysis with the entropy weight method. Using a central composite experimental design, three levels of Welding Current (I), Welding Time (T), and Electrode Force (F) were tested. The results provide a thorough welding quality index using failure energy, tensile shear load, nugget diameter, and maximum displacement. The correlation between welding quality and process variables was determined using a regression model. According to the research, welding current is the main factor affecting heat input.

Researchers Chen et al. [69] investigated how the size of the weld nuggets affected the mechanical properties and failure modes of Ti-1Al-1Mn ultrathin foil microscale RSW. Interfacial and pullout failure mechanisms were identified during tensile shear experiments. Pullout failure of welds was associated with better mechanical characteristics. According to the study, weld nugget size is a crucial component in identifying the failure mechanism. A modified model based on distortion energy theory is suggested for precise prediction. Experimental results demonstrated consistency with the proposed model, ensuring reliable determination of critical weld nugget sizes. Wan et al. [70] focused on monitoring small-scale RSW of TC2 Ti alloy using dynamic resistance and NN. According to the study, changes in welding current impacted dynamic resistance and nugget growth, with the second resistance peak decreasing. Variations in dynamic electrical signals showed weld ejection, while the growth of nuggets correlated significantly with resistance valley and end resistance. An accurate estimation of the weld quality was made by an NN using features from the dynamic resistance curve.

A composite beam with a thickness of 0.8 mm and constructed of sheets of Ti Grade 2 and Grade 5 joined together using RSW was evaluated for its bending load capabilities by Lacki and Niemiro [71]. Strength testing and microstructure analysis were used to select the welding settings. The plastic strain distribution, load capacity, and destruction mechanism were evaluated for joints with single and parallel welds. Results indicated larger plastic strain on Grade 2 Ti sheets and undamaged RSW welds during three-point bending. The ideal welding parameters for Ti–1Al–1Mn thin foils (0.05 mm thick) employed in Small-Scale Resistance Spot Welding (SSRSW) were investigated by Yue et al. [72]. While other parameters stayed constant, variations in welding current (600-800 A), electrode force (8.88-35.56 N), and welding time (6-10 ms) were investigated. The Response Surface Methodology (RSM) quadratic model was used to analyze absorption energy, shear force, and microstructure.

The outcomes demonstrated that the welding parameters for SSRSW were optimized to a satisfactory degree, with microstructures varying between the welded joints and the ά-martensite base material. Figure 8 shows a three-dimensional surface that illustrates the shear force in connection to welding parameters such as electrode force, welding current, and welding time.

The development of a quality monitoring system for small-scale RSW of TC2 Ti alloy (0.4 mm thickness) was investigated by Wan et al. [73]. The features taken from the electrode voltage and dynamic resistance curves were analysed. In order to forecast the quality of the weld, neural network models were used, using failure load estimation for quality level classification and backpropagation neural networks appropriate for probabilistic NNs. The study highlighted the sensitivity of failure load and features to changes in welding current rather than electrode force. Wan et al. [74] examined multi-objective optimization of small-scale RSW of TC2 Ti alloy. The study used Grey Relational Analysis (GRA), Genetic Algorithms (GA) and Neural Networks (NN) to optimize the welding process, focusing on TC2 Titanium alloy with a thickness of 0.4mm. The welding parameters consist of time intervals of 4, 6, 8 and 10 ms, current values of 1.0, 1.4, 1.8 and 2.2 kA, and force levels of 100, 125, 150 and 175 N. The welding process employs a 3mm diameter electrode tip.

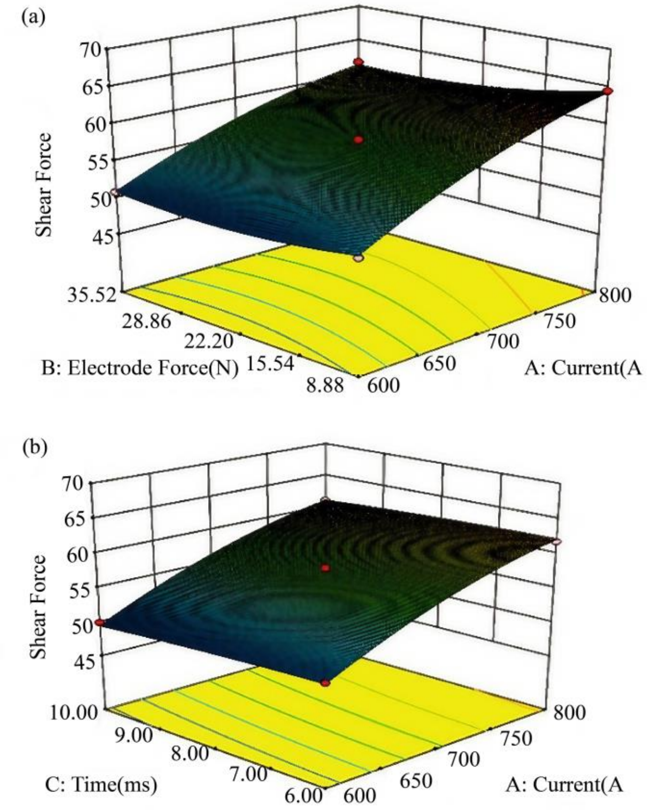

Fig. 8 Shear force's three-dimensional surface in connection to welding parameters, including electrode force, welding current, and welding time [72]

Welding current was the most significant parameter in improving weld quality, and GRA gave a rough estimation of optimal parameters. Then, the study used various architectures of backpropagation NN to predict welding quality based on these parameters and determined that failure load was more sensitive to changes in welding parameters than nugget diameter. The GA was then used to find optimal welding parameters, and good agreement was shown between predictions and experimental results. Wan et al. [75] explored the development of a quality monitoring system for small-scale RSW using dynamic resistance and NN techniques. The study focuses on TC2 Ti alloy with a thickness of 0.4mm, employing welding parameters such as time (6-12 ms), current (1.2-2.4 kA), and force (75-200 N) with an electrode tip diameter of 3mm. The study found relationships between resistance peaks and weld quality by examining dynamic resistance variations. For quality estimation, both multiple linear regression and neural network models were employed; the NN model outperformed regression analysis. In this welding process, using NNs in conjunction with dynamic resistance measurement proved beneficial for quality control.

The structure of nanostructured Ti alloy joints Ti-6Al-4V formed by RSW was investigated by Klimenov et al. [76]. X-ray structural analysis and scanning electron microscopy determined the relationship between the metal structure in the primary joint zones and the weld zone. The weld joint zone exhibited a finely dispersed martensite structure due to local heating and rapid cooling during welding. Derlatka et al. [77] used 0.8 mm-thick Ti Grade 5 sheets to investigate the load-bearing capacity of RSW joints. Five different welding parameter sets were tested, and the most effective one was chosen. Three types of joints were created using these parameters with varying weld spacings. The study evaluated plastic strain distribution, load capacity, and cracking methods. It also demonstrated the feasibility of constructing beams from these welded Ti sheets.

Wan et al. [78] investigated the quality evaluation in small-scale RSW of TC2 Ti alloy. The study identified four stages in the voltage curve by analysing electrode voltage variations and their correlation with weld quality. A NN model was proposed to evaluate weld quality based on voltage signals, and the results indicated potential for real-time quality monitoring systems. Wan et al. [79] applied Principal Component Analysis (PCA) and GA to solve a multi-response optimization problem for SSRSW of 0.4 mm thick TC2 titanium alloy. Using a central composite experimental design, the study evaluated the influence of electrode force, welding current, and welding time on weld quality indicators: failure load, nugget diameter, failure displacement and failure energy. Initially PCA was applied to combine these quality indicators into composite weld quality indexes with multiple weighted selection strategies being used. A mathematical function for predicting these weighted principal components was developed using multiple stepwise regression analysis.

Welding current was again known as the most significant factor. The optimization of welding parameters using GA was experimentally validated, with the first principal component considered the most effective quality index. When analyzing the weldability of Ti-1Al-1Mn thin foils, Chen et al. [80] focused on online monitoring and evaluating the weld quality of RSW Ti alloy. The method ensures dependable quality assessment by extracting characteristic information through real-time welding parameter analysis and acquisition. Using TB2 Ti alloy as the material with process parameters, the system detects defects such as splash and incomplete fusion during welding.

Zhao et al. [81] exposed the optimization of failure energy in spot-welded Ti alloys. The study developed a mathematical model correlating welding parameters (welding current, electrode force and welding time) with failure energy using Box–Behnken experimental design with 17 tests based on Response Surface Methodology (RSM). The RSM model enabled the analysis of both individual and interaction effects of welding parameters on failure energy. A sensitivity analysis displayed the influence of each parameter on joint quality. The study further optimized process parameters using the Artificial Fish Swarm Algorithm (AFSA), which successfully identified the combination of parameters that maximized failure energy. Verification tests with new welding parameters established the RSM model’s robustness and effectiveness. Li et al. [82] investigated the microstructure and mechanical characteristics of Al/Ti joints welded by RSW. Commercially pure Ti (TA1) and aluminium alloy 6061-T6 sheets were spot welded. The findings showed the crucial welding current range, which affects the quality of the weld joint, where the reaction changes from solid to liquid titanium. Because the titanium stayed solid and the aluminum alloy melted, the Al/Ti junction displayed a brazed joint structure. While welding duration and electrode force had little effect on tensile shear characteristics, welding current had a substantial influence. In their study, Hou et al. investigated the mechanical properties and microstructure of RSW joints consisting of pure Ti and stainless steel (SUS304) with an Nb interlayer [83]. Titanium and 304 stainless steel sheets were sandwiched together with nitin foil. The interfacial microstructure revealed the eutectic structure of Nb and FeNb. The study investigated how welding current affected the tensile shear stress and nugget diameter; the greatest load of 5.61 kN was attained at ten kA. This illustrated how well RSW joins Ti and stainless steel with Nb interlayer. Figure 9 displayed the nugget diameter and tensile shear force as functions of welding current.

Electrode wear was evaluated by Mathiszik et al. [84] during the RSW process without the use of additional sensors to determine the optimal timing for tip dressing based on process data rather than experience. The electrode wear modes, such as mushrooming and plateau forming, were analyzed under laboratory conditions using topographical measurements.

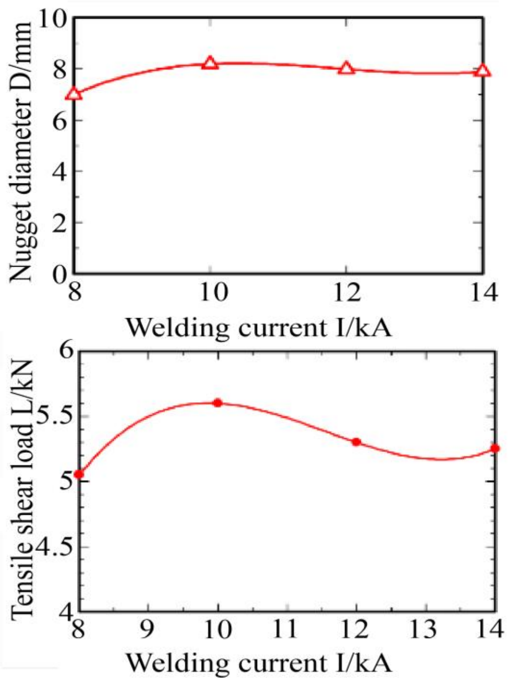

Fig. 9 Welding current impact on nugget diameter and tensile shear load [83]

The study discovered that electrode wear leads to deformation of the electrode contact area, which impacts weld quality and process parameters. However, the limitation is the wear detection method’s importance on electrode length delta, which might not consider all aspects of wear, such as surface changes or material buildup. The influence of current pulse width on electrode wear during RSW of aluminum alloy 6016-T4 was studied by Schulz et al. [85]. The study shows increased surface roughness and electrode erosion with a longer pulse time. The decrease of current pulse width decreased electrode wear without losing joint quality by reducing surface temperatures. While decreasing the current pulse width was shown to minimize electrode wear, which may not be suitable for all applications. Also, it impacts weld penetration in thicker materials and affects the ability to produce larger welds.

Table 4 summarizing the key aspects of the proposed review and previous reviews. The proposed review stands out by providing a comprehensive overview of RSW focused on Ti and its alloys, covering alloy composition, surface preparation, nugget formation and process parameters. In contrast to existing studies that focus on general welding techniques (Reddy et al. [86]), dissimilar material welding with interlayers (Liu and Zhang [87] and Giri et al. [90]) and RSW in steels and other alloys (Soomro et al. [88]). However, this review uniquely highlights the need for further research on specific titanium alloys like AMS 4902 and the optimization of RSW for thicker sheets, which provides industrial relevance and future research direction in the field, which is exceeded by studies on other metals.

Table 4. Comparative analysis of reviews on welding techniques for Ti, Ti alloys and dissimilar material joints

Study	Focus Area	Welding Methods	Materials	Research Gaps / Future Directions
Proposed Review	Comprehensive overview of RSW in Ti alloys	RSW	Ti and its alloys	Research on specific Ti alloys (AMS 4902), RSW for thicker sheets, electrode size optimization
Reddy et al. [86]	General review of welding techniques for Ti	Various welding methods	Ti and its alloys	Need for optimized welding methods to avoid defects in Ti alloys
Liu and Zhang [87]	Influence of interlayers on Ti/Steel dissimilar welding	RSW	Ti and steel	More research is needed on optimizing interlayer materials for better mechanical properties.
Soomro et al. [88]	Enhancing the mechanical performance of RSW joints in automotive steels	RSW, interlayer-assisted RSW, magnetically assisted RSW, pulsed RSW	Automotive sheet steels (AHSS)	Study on failure behavior and RSW process feasibility for various AHSS grades
Ariyanto et al. [89]	Optimization of RSW parameters for dissimilar materials in automotive	RSW	Dissimilar materials	Lack of review on the selection of optimal welding parameters for different material combinations
Giri et al. [90]	Welding of dissimilar Ti/SS joints	Various welding methods focus on fusion welding	Ti and stainless steel	Need for more advanced methods and process optimizations for better dissimilar metal welds.

5. Gaps in Current Studies

Several research gaps have been identified in current studies on the RSW of Ti alloys. Although much research has looked into how welding settings affect weld quality and mechanical qualities, our knowledge of how welded joints perform and last under real-world conditions is still limited. Most studies focus on a specific Ti alloy composition, such as Ti6Al4V, leaving a gap in understanding the RSW behavior of other Ti alloy compositions. Incorporating new materials or adopting novel welding procedures to solve existing obstacles and improve weld quality are two examples of innovative ways that might be studied to increase the efficiency and effectiveness of RSW processes for Ti alloys. Despite several investigations into the effects of these variables on weld quality, a dearth of complete knowledge regarding the combined influence of welding current, electrode force, and other parameters on weld qualities has been observed. There is a gap in research exploring innovative techniques to enhance the reliability, efficiency, and quality of RSW processes for Ti alloys, such as advanced monitoring and control systems, novel electrode materials, or alternative welding strategies. These research gaps could significantly advance the understanding and application of RSW for Ti alloys in various industries.

6. Conclusion and Future Directions

Based on identified research gaps, some conclusions can be drawn from the current state of research on the RSW of Ti and its alloys. Most of the research conducted on RSW for Ti and its alloys focused on sheet thicknesses less than 1mm. This shows a gap in understanding the behavior and optimization of RSW for thicker materials, which may have different welding characteristics and requirements. A major portion of the literature uses electrode diameters less than 5mm for RSW of Ti alloys. This highlights the need for research examining the effects of electrode diameter on weld quality, as different diameters may result in varied weld properties and performance. While several Ti alloys have been studied in RSW, certain alloys have a gap, such as AMS 4902. To observe a better understanding of RSW for Ti materials, it would be valuable to study these alloys’ welding behavior and properties. These results recommend that RSW for thicker Ti sheets should be part of future RSW studies for Ti and its alloys. This shows how to optimize the welding process, how joints in thicker sections behave mechanically and how to optimize the welding behavior. Focusing on the influence of electrode diameter on weld quality and performance would help to determine optimal electrode sizes for different applications and materials. Conducting research on RSW for specific Ti alloys, such as AMS 4902, would fill existing gaps in the literature and provide solutions for welding these materials. In addition, future studies will focus on the automation of RSW processes, increasing efficiency and consistency in welding operations. Real-time monitoring and control of welding parameters could develop weld quality by allowing adjustments during the welding process. Also, developing predictive models for weld quality based on varying parameters would provide understanding and tools for engineers and researchers to assist more effective and reliable RSW applications in the industry. By addressing these research areas, future studies can improve the understanding, efficiency and reliability of RSW processes for Ti and its alloys, enabling their broader application in industrial sectors.

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