

A Review on Resistance Spot Welding of Dissimilar Metal

Renu¹, Neeraj Bisht², Sonika Chauhan³, Nisha Rani⁴

Abstract

An extensive analysis of resistance spot welding in dissimilar metals is presented in this review paper. Resistance spot welding (RSW) is a joining technique that is frequently used in various sectors and most importantly in automotive sectors because of its effectiveness and efficiency in creating strong welded joints. This paper provides basic understanding of the various aspects of work done on dissimilar metals. It also gives an understanding of the factors affecting the mechanical properties and microstructure of the RSW joint. This paper also discusses the effects of filler materials on different dissimilar metal combinations and the effect of intermetallic compound layer on the RSW welded joint.

Keywords: Resistance spot welding, aluminum alloys, magnesium alloys, titanium alloys, microstructure, intermetallic compounds, failure mode, welding parameters

INTRODUCTION

Resistance spot welding (RSW) is a type of welding in which two or more overlapping metal sheets, either similar or dissimilar, are put together between two copper alloy electrodes that are subjected to regulated pressure as well as large electrical currents. The base metals are compressed by the electrodes and the electrical resistance at the metals' interface results in concentrated heating. The electrode force is maintained immediately after the current flow stops and the weld metal rapidly cools and solidifies [1–3]. Due to the minimal skill requirements, affordable equipment, simplicity of operation, versatility, high operating speeds, repeatability, suitability for automation or robotization and inclusion in high-production assembly lines, RSW is the dominant metal sheet joining process in the automotive industry. RSW is also preferred over other welding methods, because it can be used to join a wide range of metals (Qiu et al, 2011; Vural & Akkus, 2004) and hence it is one of the most suitable metals joining method in automobiles. Today, the top priority for the automobile sector is to reduce CO₂ emissions because of the current environmental issues [4]. Also, the vehicle weight reduction efforts are being made by companies to cut down on the fuel usage and most importantly the pollution. A standard car body frequently contributes nearly 30% of the total weight of a car [5] and a car's fuel economy increases by 5.5% when its weight is reduced by around 10% [6, 7]. In a modern automobile, there are typically 2000–5000 spot welds. A vehicle's mechanical characteristics, structural performance, durability, safety design, stiffness, strength and integrity all are influenced by the resistance spot welds as well as the mechanical properties of the sheets [8–10].

*Author for Correspondence

Nisha Rani
E-mail: nrani2524@gmail.com

¹Lecturer, Mechanical Engineering, Govt. Polytechnic, Bazpur.

^{2, 3}Assistant Professor, Mechanical Engineering Department, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, India.

⁴Ph.D. Scholar, Mechanical Engineering Department, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, India.

Received Date: July 05, 2024

Accepted Date: July 12, 2024

Published Date: October 10, 2024

Citation: Renu, Neeraj Bisht, Sonika Chauhan, Nisha Rani. A Review on Resistance Spot Welding of Dissimilar Metal. International Journal of Metallurgy and Alloys. 2024; 10(1): 12–24p.

VARIOUS RESEARCH APPROACHES TO ENHANCE THE PERFORMANCE OF DISSIMILAR METAL WELDS

Study of IMC Layer

In dissimilar resistance spot welding, an intermetallic compound layer refers to a thin layer of a compound that forms at the interface between two dissimilar metal sheets or parts that are being joined together through the process of resistance spot welding. The specific intermetallic compounds that form during dissimilar resistance spot welding

depend on the composition of the metals being joined and the welding conditions, such as temperature, pressure and welding time.

Interlayers Used

Sun et al. (2015) introduced a new method for preventing formation of intermetallic compound layer (IMC) between Al (AA5754-O)–Mg (AZ31B-H24) dissimilar joining [11, 12]. A 0.2 mm thick commercial pure nickel foil was used as an interlayer between Al-Mg. Major focus was on nugget shape, micro structural observations, mechanical properties and fracture characteristics of the welds. The microstructure of Mg/Ni interface, microstructure of Al/Ni interface was also investigated. Investigation was also done on the microstructure with the help of SEM/EDS and XRD methods. It was concluded that the formation of Al-Mg brittle intermetallic compound can prevent and quality of weld joints and can be improved by using a pure nickel foil as an interlayer. It was also observed that the welding current directly affects the nugget size and the welding defects. With increase in the welding current, large size nugget diameter and welding defects such as cracks, porosity etc. was observed in the Mg/Ni interfacial area.

Sun et al. (2020) investigated the resistance spot welding of dissimilar aluminum (AA5052) and magnesium (AZ31) alloys. The aim of their investigation was to prevent the formation of undesirable Al-Mg intermetallic compounds and to achieve strong Al-Mg welded joints. A Sn-coated steel interlayer was utilized for this purpose. The successful prevention of intermetallic compound formation led to robust joints with 88% increase in the tensile shear strength of Mg-Mg joints. Failure occurred within the Al fusion zone during mechanical loading, indicating limited influence of the thin Al-Fe reaction layer at the Al-steel interface. In direct Al-Mg welding, brittle intermetallic phases (Al_3Mg_2 and $Al_{12}Mg_{17}$) were formed, causing preferential failure through these regions and compromising the mechanical properties and reliability of joints.

Lu et al. (2019) introduced a new joining method for dissimilar metal, named Ultrasonic plus resistance spot welding. Aluminum alloy A6061-T6 was welded to cold-rolled 1008 steel by Ultrasonic plus resistance spot welding and the microstructure and mechanical properties of the formed joint were studied [13]. The study especially focused on the impact of U+RSW parameters on the interfacial microstructure, nugget size, joint strength and failure mode of the welded joints. Ultrasonic spot welding was used to make an intermediate joint between a thin aluminum insert and steel. Then resistance spot welding was used to make an intermediate joint to aluminum sheet. Temperature distribution during resistance spot welding was also studied with the help of simulation. Results of this study show that a nugget is formed on aluminum side whereas a heat affected zone is formed on the steel side. It was observed that at the weld center the maximum thickness of the IMC layer was created. The joint efficiency for this method was found to be 61%. Four types of failure modes namely, shear fracture, full nugget pull-out from insert, nugget pull-out from Al sheet, interfacial fracture through Al insert/steel interface were seen and it was found that all failure modes were affected by welding current.

Arghavani et al. (2016) focused on, the effect of zinc layer on the microstructure and mechanical properties of Al-5052, St-12 (DC 01) and low carbon galvanized (ASTM A653 CS Type B-G60) joints [14]. The cross-section of weld and diameter of the nugget of Al-Fe intermetallics were investigated. The investigation concluded that during current supply, melting is seen only in aluminum sheet, and it formed weld nugget. When compared to GS-Al joint, larger weld nugget was formed in PS-Al joint. Low welding current results in decrease in strength because of incomplete joining at GS-Al sheet. It was also seen that the thickness of intermetallic compound layer was more than the critical value in PS-Al joints. Thicker IMC layer decreased the mechanical strength of the joints because of the brittleness of the intermetallic. It was also found that the failure mode was interfacial mode. In PS-Al as well as in GS-Al joints crack start increasing from periphery to IMC layer and then center of the weld nugget.

Hendrawan et al. (2021) used zinc powder as an intermediate material between 1.2 mm thick 4000 series aluminum and 0.9 mm thick AISI 1008 mild steel to examine the mechanical parameters of dissimilar metal joint made by resistance spot welding [15]. Shear tests of the joints were done to study

the macro and micro-structures. Results show that change in welding current affects the shear strength of weld joint and width of weld metal diameter. Increase in the welding current increases the weld diameter of weld metal. After complete testing the optimal value of current and welding time was 9000A and 0.5 s. Results of Vickers hardness test showed that for current 7000 A time 0.5 s an average hardness value was 152.0 HVN for mild steel welding and 110.0 HVN for aluminum welding. For current 8000 A at 0.5s average hardness value of 172.7 HVN for mild steel welding and 112.0 HVN for aluminum. The current variation of 9000 A at 0.5 s has an average hardness value of 224.7 HVN on mild steel and 154.3 HVN weld metal.

Chen et al. (2017) focused on failure modes, weld strength, microhardness, intermetallic compound thickness and fracture mechanism of dissimilar metal spot welds joint. For this, a 1.2 mm thick aluminum alloy AA6022-T4 sheet and 2 mm thick hot dipped galvanized low carbon steel sheet (HDG LCS) were joined together by resistance spot welding with 6 different welding schedules and then lap shear tests were performed. Results show that mainly three types of fracture mechanism and failure modes occurred which are brittle fracture in IMC layer, cause of interfacial failure, ductile fracture in aluminum fusion zone cause of thickness failure and ductile fracture in aluminum HAZ cause of pullout failure. Thin IMC layer of less than 3 μm caused the button pullout failure. IMC layers that were thicker than 3 μm experienced interfacial failure. High welding current in a short welding period enabled the growth of Al nuggets while keeping IMC thickness to a minimum, significantly improving the overall mechanical performance. The measurement and characteristics of the IMC layer, aluminum FZ and aluminum HAZ had a major effect on the weld's failure scenario and mechanical strength [16–18].

Wan et al. (2017) focused on the interfaces of Al alloy 6022-T4 sheet and 60G hot-dip galvanized mild steel dissimilar metal joint. Experimental study was done on the characterization of the intermetallic compound (IMC) layer at the Al-steel interface, formation mechanism of the two types of IMC layer. Analysis of IMC thickness distribution was done based on different welding parameters like effect of welding time and effect of welding current. It was observed that up to peak value of welding current, the increase in welding current increases interfacial area of the thick IMC and two types of IMC layer present at the interface of the joining metals. One was found in the center of the interface, made up of Fe_2Al_5 that resembles a tongue next to the steel and FeAl_3 that resembles serrated edges next to the aluminum and the other was a combination of FeAl_3 and aluminum, located on the edges of the joint interface [12].

Qiu et al. (2009) focused on the tensile shear strength and microstructure of resistance spot welded joints obtained by using a cover plate and focused on the effect of reaction layer and nugget diameter on the tensile shear strength of the joints. This study was done on dissimilar metals aluminum alloy A5052, cold-rolled steel SPCC, and austenitic stainless steel SUS304. Cover plates were used at the direct contact of movable electrode. Results of interfacial microstructure study show that at the interface of A5052/SPCC and A5052/SUS304 two types of reaction layer occurred which are thick two layers and thin serration layer. Both contain Fe_2Al_5 and FeAl_3 . The change in thickness of the reaction layer was due to the combination of materials and welding current. In case of A5050/SUS304 joint, there was no change in tensile shear strength because reaction layer was found unlike in A5052/SPCC, in which the tensile shear strength was affected by the reaction layer [6].

Shi et al. (2019) derived a new formula for calculation of critical aluminum-steel weld nugget diameter based upon experimental results. The major focus of this study was on fracture modes of dissimilar resistance spot welds joints. Materials used for this study were 0.8-mm thick X626-T4 aluminum alloy, 1.2-mm thick AA6022-T4 aluminum alloy, 0.9mm and 1.2-mm thick hot dipped galvanized (HDG) low carbon steel (LCS) sheets. Weld joints were created by multi ring domed (MRD) electrode and multiple solidification weld schedules. Results of tensile test conclude that interfacial and pull-out fracture types of fracture modes have occurred in the specimens. In case of Al and steel welded joints, formation of IMC layer is the main factor for affecting the fracture mode. The formula given for

calculation of critical weld nugget diameter in tensile shear specimens in this study is $d_{cr} = 4\beta(1 - \varepsilon)t$, where $\beta = \tau_{HAZ}^f / \tau_{IMC}^f$, τ_{HAZ}^f and τ_{IMC}^f are the shear strengths of the HAZ and IMC layer, respectively, t is the thickness and ε is the thickness reduction ratio [19].

Al-Filfily et al. (2020) focused on the strength of aluminum alloy AA6061 and carbon steel RSW joint with and without filler materials by using resistance spot welding. Copper and zinc were used as filler material. Results show that the use of filler materials results in better joint strength. For AA6061 and carbon steel filler material copper gave higher strength of joints as compared to zinc. The effect of welding current is more as compared to welding time on the strength of the joints.

Hu et al. (2020) worked on joining of two dissimilar metals by using resistance spot welding with multi ring domed electrode and multiple solidification weld schedules. This study deals with the comparison between AA6022-HDG LCS weld joints and AA5754-HDG LCS weld joints. For investigation of impact of aluminum contact resistance on AA5754-LCS and AA6022-LCS weld macrostructure, analysis of interfacial microstructure, defect distribution and coach peel test has been done. Results of this study conclude that in AA6022-HDG LCS welds, planer and thin intermetallic compound (IMC) layer is formed and in AA5754-HDG LCS welds, less planer and thicker intermetallic compound (IMC) layer is formed. In case of AA5754-O, small size nugget but in case of AA6022-T4 large size nugget observed. The oxide layer was present in the solidified weld structure above the faying interface in AA5754-HDG LCS welds but was absent in welds made of Al-steel using either AA5754 or AA6022. During mechanical testing, the oxide film imperfections functioned as low-energy crack propagation site [20].

Kang et al. (2020) studied microstructure and shear strength of resistance spot weld joints in dissimilar metal. They also focused on macrostructure, micro hardness, maximum tensile loads and shear strength of intermetallic layer. For this study 1.2 mm thick wrought aluminum alloy AA6022-T4, 2 mm thick hot-dip galvanized interstitial free steel was used. Welding was done by using multi ring domed electrode (MRD) and multiple solidifications weld schedules. A new test method was developed for the measurement of shear strength of intermetallic layer formed at joining surface. Results show that two different intermetallic layers occurred, a needle-like $FeAl_3$ at the interface of AA6022-T4 sheet and a tongue-like Fe_2Al_5 at the hot-dip galvanized interface of IF steel sheet. At the periphery of nugget, thickness of intermetallic layer was 2 μm . In comparison to the asymmetrical electrode combination, the symmetrical electrode combination generated a considerably more uniform response in terms of intermetallic layer shear strength [21, 22].

Kapil et al. (2020) worked on creating a new approach for dealing with the joining of dissimilar metal aluminum-steel impact spot welding by the help of vaporizing foil actuators. This approach enabled us to join Al alloy (AA6111-T4 and aural 2) to three types of HSLA 340 steel (bare, galvanized and e-coated). Mechanical testing and metallographic analysis of the joint has been done in this study. Under mechanical testing, lap-shear and coach peel testing were included. Results show high strength of the joint with button pullout failure modes in all samples. Defect-free joints were found in testing of weld cross section [23].

Liu et al. (2020) have done analysis on dissimilar joining of Q235 mild steel and TC4 titanium alloy with interlayer and without interlayer of filler metal with Ni-Cu alloy. They have also studied interfacial properties, microstructure, macro-characteristic and mechanical properties using interlayers. It was observed that a reaction and diffusion layer occurred in joining of TC4 and Q235 with interlayer [3].

Shi et al. (2020) presented an experimental investigation and simulation work on effect of notch root angle on fatigue behavior of dissimilar metal (1.2mm thick AA6022-T4 and 2 mm thick hot dip galvanized steel) resistance spot welds joint. For the complete investigation a multi-ring domed (MRD) electrode and multiple-solidification weld schedules with aluminum in both the positive and negative polarity conditions were used to create different aluminum-steel RSWs.

Structural features of joints, microhardness measurement, Shear strength of intermetallic layer and tensile property, fatigue behavior and DIC validation of principal strain calculations. Impact of weld geometry on fatigue life and fatigue fracture mode has been also studied. Results of both experimental and simulation studies conclude that any changes in weld polarity directly show variation in notch root angles. In both polarity conditions, it is observed that IMC layer thickness is about 1.2 μm but microhardness of the nugget and heat affected zone is less in negative polarity condition. Thickness of IMC layer up to 2 μm on the edge of nugget, for both polarities same shear strength of the intermetallic layer. Increases in notch root angle results increase tensile load, better fracture modes and helpful to improve fatigue life and decrease in principal strain. The pull-out fracture mode was also supported by increasing the notch root angle [22, 24, 25].

Mishra et al. (2021) focused on weld nugget size for dissimilar metal joining of mild steel and stainless steel by resistance spot welding. Different input process parameters like welding current, thickness of sheet, etc. were studied. Thicknesses of metal taken were 0.8 mm, 1 mm, 1 mm, 1.2 mm and electrode diameter were 6 mm. They have done analysis of response mean value and response signal to noise (SN) ratio value of weld nugget diameter. For optimization of factors Taguchi L9 orthogonal approach was chosen. Results of this experiments showed that quality and strength of spot weld joint directly linked with materials properties, thickness and size. Weld current is a very important factor to create a high-quality joints and changes in input parameter current showed changes in output parameter weld nugget diameter. It was also concluded that for estimation of selected factors and levels desirability function was used and maximum desirability was achieved 0.98. According to desirability function to join 1.2 mm thick metal sheet required current was found as 9500 A and nugget diameter was measured to be 4 mm [26].

Taufiqur Rahman et al. (2021) studied the effect of holding time on dissimilar metal joint created by resistance spot welding. For this study, stainless steel 316L and Ti6Al4V titanium alloy were used. To achieve better weld quality aluminum was used as an interlayer in between the joining metals. The objective of the study was to analyze the mechanical and physical properties of the welded joints. A thin reaction layer created on the intermetallic compound of the SS316L/AA5754 interface, and a diffusion-reaction found on the AA5754/Ti6Al4V interface. A crosssection was helpful for finding voids in welding zone and it was observed that the weld strength is directly affected by the voids present in weld nugget area. Increasing the holding time resulted in decrease in voids and hence increase in the strength of welded joints [27].

Chen et al. (2016) examined the microstructure and mechanical properties of a resistance-spot-welded joint between A5052 aluminum alloy and DP 600 dual-phase steel. In the DP 600, the fusion zone (FZ) displayed lath martensite, while the heat-affected zone (HAZ) exhibited ferrite-martensite structures. On the A5052 side, the FZ and HAZ microstructures featured cellular crystals, with columnar crystal morphology at the FZ boundary. Notably, adjacent to DP 600 was a 3.3 μm Fe₂Al₅ intermetallic compound (IMC) layer, while the aluminum alloy side displayed a needleshaped Fe₄Al₁₃ IMC layer ranging from 0.67 μm to 15.8 μm . The joint's maximum tensile shear load was 5.5 kN, aligned with a 6.3 mm molten nugget diameter. Fracture morphology of the optimized joint was primarily elongated dimple fractures along with cleavage fractures [28].

Chen et al. (2022) observed how welding current and welding time affected the shearing strength of joints made by resistance spot welding low carbon steel and stainless-steel plates. The macro properties, microstructure and micro-hardness of welded joints were also studied. Results of this study concluded that the RSW joints with the maximum shearing strength 7504.67 N had a welding current of 10 kA and a welding time of 80 ms. Five different regions were found in microstructure study of RSW joints: the nugget, the course HAZ, the fine HAZ, the base material low-carbon steel and base materials of stainless steel. Large size nugget observed on the stainless-steel plate side compared to low carbon steel side. The nugget and coarse HAZ have a greater micro-hardness than the fine HAZ and base materials.

The large variations in micro-hardness between RSW joints and base materials on the side of low carbon steel were identified as the reason for the peeling fracture. The poor load capacity of small RSW joints was the root cause of the shearing-off fracture [29].

Oliveira et al. (2019) research employed a multi-process approach, combining resistance spot welding with friction element welding, to create a three-sheet stack using advanced high strength steel and precipitation hardened aluminum. The individual and combined weld processes were examined to assess their impact on joint performance. Microstructural and mechanical evaluations, including scanning electron microscopy and nanoindentation, were conducted on weld interfaces and heat affected zones. Results consistently demonstrated strong strength above maximum breaking force thresholds, irrespective of offset distances between the two weld types. A shift in fracture mode occurred: interfacial fracture at offsets below 7 mm and nugget pull-out or partial thickness failure at offsets above 7 mm. This study shows that hybrid joining techniques minimally influence both mechanical and microstructural properties, offering potential for novel dissimilar metal weld designs in the automotive industry.

Shi et al. (2022) studied about the effects of specimen configuration and notch root angle on the fatigue behavior of the weld's joints. Weld joints were created between dissimilar metals AA5754 and HSLA steel by using resistance spot welding. Whenever steel and aluminum is joined by RSW it was seen that, an intermetallic compound layer formed at the interface of aluminum and steel and this layer directly affects the strength of the RSW joints. To achieve better strength of the joints multi ring domed electrode and multiple solidification weld schedules were used. In structural stress analysis for fatigue life two tests were conducted, namely Lap shear and coach peel which showed that nugget diameter plays a key role for fatigue life because change in nugget diameter directly affects the fatigue life of the joints. Finite element analysis also showed that the notch root angle is directly related to fatigue life and principal strain because large root angle is responsible for longer fatigue life and less maximum principle strain [30].

Guzanová et al. (2023) tried to join steel to an aluminum alloy applying a unique resistance spot welding technique with an insert element made of anticorrosive steel in combination with adhesive bonding. The hybrid joining method was used for the joining of two dissimilar materials. Short welding periods and various chemical compositions of the insert element were used in the procedure to reduce the growth of brittle intermetallic compounds. Deep-drawing low-carbon steel, HSLA zinc-coated steel and aluminum alloy 6082-T6 were used in this study. For adhesive bonding, two different types of adhesives, one based on rubber and the other on epoxy resin, were chosen. Study focuses on the evaluation of substrate micro geometry, load carrying capacity of the joints, SEM analysis of joints. Analysis of load carrying capacity of the joints created by RSW, joints created by RSW and rubber-based adhesive bonding, joints created by RSW, and epoxy-based adhesive bonding was done. The load capacity of joints created using resistance spot welding with a rubber-based adhesive was found around 6 kN, whereas joints created with an epoxy-based adhesive had a load capacity equal to the maximum load of the substrate (Al-DC: 10 kN; Al-TL: 12 kN). Whether they were Al-DC or Al-TL joints, connections created by resistance spot welding with the insert element alone were able to withstand up to 1800 N of force because to the narrow contact area [31].

Liu et al. (2023) focused on mechanical properties and failure mode of the RSW joint of medium Manganese TRIP Steel with DP590 and welding process test with numerical analysis of the plates. Firstly, they did experimental analysis and numerical simulation of the RSW. Then they compared the results of both. From comparison nugget diameter error was calculated approximately 7% for accuracy and reliability of RSW finite element model. Experimental analysis was done on effects of welding current on the mechanical properties and failure mode of the joints. Numerical simulation was done on thermo physical parameters of plate, geometry and boundary condition. Results of simulation showed that at the starting time of welding stress concentration occurs in 7MnSteel heat-affected zone at the

edge of the electrode in welding plate, it can be the cause of failure of the joint. At optimal welding current 9 kA, diameter of weld nugget was 8.53 mm and maximum value of tensile shear was 11.14 kN. The welds were observed to undergo interface failure (IF), partial interface failure (PIF), pull-out failure (PF), and partial pull-out failure (PF-TT) [32].

Manladan et al. (2023) investigated lap shear performance of resistance spot weld joints in case of dissimilar metal. 1.5 mm thick aluminum alloy 5754 and 1.5 mm 420 martensitic stainless steel were joined using RSW. It was found that columnar grain structure exists in aluminum nugget microstructure. The interfacial compound layer was available in two layers at the aluminum alloy nugget/martensitic stainless-steel interface. On the MSS side tongue-like morphology Fe_2Al_5 layer and on the Al side serrated-like morphology FeAl_3 layer was observed. Minimum thickness of the IMC layer was at the nugget periphery, increasing when moving away from periphery and maximum at center of nugget. Failure generates from Fe_2Al_5 IMC layer. From variation in current, it was concluded that for all currents, mode of the failure was interfacial failure and maximum energy absorption was 3.73 J and maximum peak load 4.39 kN.

Qiu et al. (2023) have done work on improvement of the performance of A6061 aluminum alloy and Q235 mild steel resistance spot welded joints using a different type of electrode named as embedded composite electrode. They also performed normal RSW for a comparative study with common electrode with rest parameters as same. The morphology of the joint cross-section, metallographic structure of nugget, microstructure of the interfacial zone and the joint performance were studied. Tensile shear test for tensile strength, for microstructure of joints SEM (scanning electron microscopy) test and for analysis of the reaction product energy dispersive X-ray spectroscopy (EDS) test were performed. When resistance spot welding was done with composite electrode, it was observed that an acetabuliform nugget and a ring nugget were formed at the interface of aluminum alloy and mild steel side respectively. In case of RSW joint formed with composite electrodes, it was found that a reaction layer was available at the joint interface of A6061 AA/Q235 MS. It was observed that for welding current of 26 kA the maximum tensile shear load of 5.86 kN was achieved [33].

Shi et al. (2023) focused on different aspects of resistance spot welded joints and interfaces between dissimilar metals. The materials investigated were AA5754, HSLA 340 grade and LCS CR3 grade sheets, using MRD electrodes and various weld schedules. Microstructural analysis was carried out with both positive and negative polarity, revealing average weld nugget diameters of 7.9 mm, 7.5 mm and 7.4 mm for AA5754-HSLA and AA5754-LCS RSWs. Notch root angles were asymmetrical in AA5754-HSLA RSWs but symmetric in AA5754-LCS RSWs. Thinner intermetallic compounds formed at the weld periphery compared to the center of the weld faying interface, with AA5754-HSLA RSWs showing thinner layers than AA5754-LCS RSWs. Tensile properties indicated greater strength in Al-steel RSW joints than in AA5754-AA5754 joints. Fatigue life was longer in Al-steel RSWs, correlated with structural stress analysis and notch root angle. Increasing the notch root angle reduced maximum principal strain and extended fatigue life. Overall, the study elucidates critical factors influencing mechanical and fatigue properties of dissimilar metal RSW joints [34].

Winnicki et al. (2018) explored the resistance spot welding (RSW) of aluminum alloy AA5754 to DC01 steel, employing various interlayers including aluminum-alumina, aluminum-nickel-alumina and nickel-alumina coatings deposited through LPCS method. Microstructural analysis post-RSW revealed that only $\text{Ni} + \text{Al}_2\text{O}_3$ interlayers retained their original form. $\text{Al} + \text{Al}_2\text{O}_3$ interlayer exhibited integration of aluminum powder with the base material, while thick coating led to intermetallic phases. $\text{Al} + \text{Ni} + \text{Al}_2\text{O}_3$ interlayers caused exothermic reactions and Al-Ni intermetallic phases. Microhardness varied across joints, with the highest value observed in $\text{Al} + \text{Ni} + \text{Al}_2\text{O}_3$, attributed to intermetallic compound formation. Tensile shear tests favored the 250 μm $\text{Ni} + \text{Al}_2\text{O}_3$ interlayer, yielding comparable shear strength to aluminum joints and indicating enhanced joint strength. The study showcases the potential of cold spray technology for achieving mechanically sound dissimilar aluminum-steel joints [35].

Chen et al. (2018) investigated Al/steel resistance spot welding, revealing how process parameters affect microstructure and mechanical properties. Higher welding current reduced dendritic grain formation and shrinkage, while longer welding time influenced grain structure. An iron phase in the thin IMC layer improved crack resistance and load bearing at the Al/steel interface. Fracture modes included IMC layer interfacial fracture, partial thickness fracture within the Al nugget and partial button pullout. Coach peel test samples consistently showed partial button pullout. Crack initiation in cross tension occurred in the IMC layer, while coach peel often started in the Al fusion zone. Enhancing mechanical performance involved reducing Al thinning, enlarging Al Nugget size and controlling IMC layer growth, thereby modifying load-displacement curves and improving fatigue behavior. This study offers insights into optimizing Al/steel resistance spot welding for improved joint integrity [36, 37].

Ibrahim et al. (2016) focused on dissimilar welding of A6061-T6 aluminum alloy to 304 stainless steels, using an Al–Mg alloy interlayer via resistance spot welding (RSW). Efficient welding was achieved, resulting in higher tensile shear force compared to interlayer-free joints. A uniform 2 μm intermetallic compound (IMC) layer formed, enhancing bonding strength, with magnesium diffusion extending up to 5 mm into the Al sheet. RSW Al/steel welds exhibited superior tensile shear and fatigue strengths compared to friction stir spot welds (FSSW). Fatigue fracture modes varied with load levels, transitioning between plug, shear and upper Al sheet fractures, influenced by nugget rotation. Successful utilization of the Al–Mg interlayer achieved robust dissimilar welds, improving mechanical properties and fatigue behavior [38–40].

Penner et al. (2014) focused on Al/Mg dissimilar welds using resistance spot welding (RSW) with Zn foil and Zn-coated steel interlayers. Poor strength outcomes resulted from Zn foil due to brittle intermetallic phase formation. The use of a Zn-coated steel interlayer prevented alloy mixing, yielding significantly stronger welds. Achieved load capacity reached 74% of similar AZ31B joints, meeting AWS D17.2 standards with welding currents of 28 kA and higher. Similar mechanisms occurred at Al/steel and Mg/steel interfaces, divided into weld brazing, solid-state welding and soldering regions. Fusion nugget area showed Al-steel bonding through a continuous Fe–Al intermetallic layer, while Mg-steel bonding utilized an ultrathin prefabricated Fe–Al intermetallic layer. This comprehensive investigation provides valuable insights into enhancing mechanical properties and weld quality in dissimilar Al/Mg welds [41].

Wan et al. (2016) introduced an enhanced model for resistance spot welding (RSW), incorporating improved Electric Contact Resistance (ECR) and Thermal Contact Resistance (TCR) representation. The model's validation in an Al 6022-T4 to zinc-coated steel RSW process displayed high accuracy in predicting voltage response, nugget growth, joint deformation and Intermetallic Compound (IMC) formation. The model effectively reflects mechanical, electrical and thermal behaviors, with sequential coupling calculation sufficiently representing their interactions. Investigation of heat generation and consumption highlighted significant contributions from contact resistances during preheating and emphasized the role of thermal contact resistance in heat redistribution. Al-steel weld strength relies on Al nugget size and IMC thickness, with distinct nugget growth patterns attributed to heat distribution. The improved contact resistance representation enhances process modeling accuracy, aiding in predicting nugget dimensions, IMC profiles and optimizing weld schedules for desired outcomes [42].

Chen et al. (2017) enhanced the microstructure and mechanical properties of resistance spot-welded joints between DP 600 advanced high-strength steel and A5052 aluminum alloy, employing a 50 μm Zn slice interlayer. Findings indicated a columnar crystal pattern in the fusion zone (FZ) of A5052 and coarse-lath martensite in DP 600's FZ, contrasting with fine martensite in the heat-affected zone (HAZ). The intermetallic compound (IMC) at the interface encompassed Fe₂Al₅, Fe₄Al₁₃ and Fe₁₁Zn₄₀, predominantly in a winding pattern, contributing to enhanced mechanical properties. Tensile-shear load peaked at 7.06 kN, marking a 28% improvement compared to interlayer-absent cases. Pre-fracture

plastic deformation was evident, with a plug failure (PF) mode dominating over interfacial failure (IF) mode. Fracture surfaces exhibited numerous dimples. This study underscores the efficacy of the Zn slice interlayer in elevating joint strength and deformation characteristics in resistance spot-welded DP 600 and A5052 joints [43-45].

Sun et al. (2016) investigated dissimilar resistance spot welding between 16Mn high-strength steel and 6063-T6 aluminum alloy, varying welding electrodes and parameters. Aluminum alloy nuggets exhibited diverse crystal structures with tangled dislocations and fine Mg₂Si particles. Intermetallic compound layers (Fe₂Al₅ at steel side, Fe₄Al₁₃ at aluminum side) formed in the interface zone, impacting joint strength. Excessive Fe-Al compounds reduced joint strength. Welding electrode morphology and parameters significantly affected joint performance. With F-type electrodes, optimized parameters yielded a tensile shear load of 2534 N and 28.0% indentation ratio. Using optimized electrodes increased joint strength to 3623 N, reducing indentation ratio to 18% by improving temperature distribution. Employing optimized electrodes enhances steel-aluminum joint strength and appearance quality [46, 47].

Bi et al. (2016) focused on dissimilar aluminum alloys 2219/5A06 with unequal thicknesses during the resistance spot welding (RSW) process. Shunting experiments involving two multiple spot welds with varying weld spacing were conducted. Numerical simulations using ANSYS were employed to analyze the shunting effect. Results revealed that increasing weld spacing is ineffective in mitigating the shunting effect for dissimilar aluminum alloys with significant thickness differences, owing to aluminum alloy's low bulk resistance. Thus, raising welding current is the preferred strategy to counter the shunting effect. In multiple spot welds, the shunting effect is influenced by both weld spacing and specimen temperature, alongside other consistent welding conditions. This work provides insights into optimizing RSW processes for dissimilar aluminum alloys with unequal thicknesses, highlighting the importance of welding current adjustment over increased weld spacing [48, 49].

Hu et al. (2021) explored resistance spot welding of AA5754-O aluminum alloy to low carbon steel sheets using Multi-Ring Domed (MRD) electrodes in a coach peel configuration. The process revealed a linear relationship between C-gun stationary arm deflection and force applied by the movable arm. Electrode rotation during deflection caused the point of electrode-coupon contact to shift inwards, resulting in asymmetric weld features. Aluminum weld nuggets near the weld gun exhibited softer thermo-mechanically affected zones, fewer defects and thinner intermetallic compound (IMC) layers. These welds demonstrated higher button pull-out strength and absorbed 36% more energy under directional load. The cause of these asymmetries was linked to variations in electrode-workpiece contact due to weld gun deflection. Overall, this work sheds light on the effects of electrode rotation on resistance spot weld characteristics and performance.

Hayat et al. (2011) investigated resistance spot welding for joining magnesium AZ31 and aluminum 1350 alloy sheets using varying weld currents (22 kA to 33 kA). Nugget geometries were analyzed with SEM, revealing differences on aluminum and magnesium sides. Higher current and duration increased nugget size and weld strength, up to 29 kA. Fracture modes identified were "pull out" at high currents and "partial interfacial" at low currents. EDS analysis showed changing Al% and Mg% ratios in fractures with increasing current, indicating elemental distribution shifts. Increasing current increased nugget diameter and indentation, more pronounced in Al alloy due to lower strength. Beyond 29 kA, excessive melting and pressure caused splashing, reducing joint strength. Increasing current and duration improved weld strength and size, but excessive melting and magnesium presence lowered joint quality. SEM, EDS, and tensile tests provided insights into behavior of spot-welded joints between these alloys.

Zhang et al. (2015) a new technique for resistance spot welding dissimilar materials, specifically 6008-T66 aluminum alloy and H220YD galvanized high strength steel, was introduced. The focus was on optimizing the design of welding electrodes, which played a crucial role in the welding process and joint quality. Comprehensive analysis was conducted, covering macrostructure, microstructure, and

mechanical properties of the welded joints achieved using these optimized electrodes. To improve the welding process, numerical simulations were carried out to study current density distribution and temperature fields during welding. The optimized electrode configuration included a planar circular tip electrode (10 mm diameter) on the steel side and a spherical tip electrode (70 mm diameter) on the aluminum alloy side. The resulting welded joint exhibited characteristics of a specialized welded-brazed joint. An intermetallic compound layer containing Fe₂Al₅ and Fe₄Al₁₃, with a thickness of up to 4.0 μm, formed at the aluminum-steel interface. Mechanical testing showed promising results, with the welded joint achieving a tensile shear load of up to 5.4 kN when the optimized electrodes were used. Comparisons with conventional F-type electrodes highlighted the uniformity of current density distribution during welding with the optimized electrodes. Additionally, the interfacial temperature in the welded joint during the welding process using optimized electrodes was lower (approximately 915 °C) compared to F-type electrodes (about 985 °C). This study introduces an innovative approach to resistance spot welding dissimilar materials, incorporating an optimized electrode design that enhances joint quality and properties. Through a combination of experimental and numerical analyses, the research provides valuable insights into the welding process and its impact on resulting joints, contributing significantly to advancements in dissimilar material joining techniques.

Li et al. (2015) investigated the impact of electromagnetic stirring (EMS) on the microstructure and mechanical properties of Al/Ti resistance spot welds. A comparison was made with Al/Al welds, considering welding current, time, and electrode force. Traditional Al/Ti joints displayed a melted zone, columnar grains, and a transition structure. With EMS, Al/Ti joints showed a fine spheroidal grain structure, resulting in larger bonding diameter, higher tensile shear force, and energy absorption compared to traditional Al/Ti welds. The improved mechanical performance of EMS joints can be attributed to their larger bonding diameter and fine spheroidal grain structure [50].

Chen et al. (2018) developed a multi-scale finite element modeling approach to analyze deformation and fracture behavior in Al-steel resistance spot welds. Micro-scale models simulated intermetallic compound (IMC) layers with varying morphologies and thicknesses under different loads. Predicted IMC strength informed macro-scale models, predicting overall performance in coach peel, lap shear and cross-tension tests. Numerical results aligned well with experimental data, leading to these conclusions: Micro-scale models accurately predict IMC layer strength, influenced by morphology and thickness. Thinner IMC layers tend to be stronger due to increased metal remnants inhibiting crack propagation. Integrating micro-scale predictions into 3D macro-scale models enables accurate load-displacement curves and fracture mode predictions. This approach enhances the understanding of weld behavior and offers valuable insights for engineering applications.

CONCLUSIONS

The automotive industry has been regenerated by recent advances in multiple lightweight materials. But it is still difficult for manufacturers to join these dissimilar materials. The most promising steel-Al alloy, steel-Mg alloy and Al Alloy-Mg alloy dissimilar combinations have been reviewed, along with their welding-related metallurgical difficulties.

REFERENCES

1. Charde N, Yusof F, Rajkumar R. Material characterizations of mild steels, stainless steels and both steel mixed joints under resistance spot welding (2-mm sheets). *Int J Adv Manuf Technol.* 2014;75(1–4):373–384.
2. Kocabekir B, Kacar R, Gündüz S, Hayat F. An effect of heat input, weld atmosphere and weld cooling conditions on the resistance spot weldability of 316L austenitic stainless steel. *J Mater Process Technol.* 2008;195(1):327–335.
3. Liu L, Feng J, Zhou Y. Resistance spot welding of magnesium alloys. In: Liu L, editor. *Welding and joining of magnesium alloys.* Woodhead Publishing; 2010. p. 351–367.
4. Lee M, Jung S. Trends of Advanced Multi-Material Technology for Light Materials based on Aluminum. *J. Weld. Join.* 2016;34(5):19–25. doi:10.5781/JWJ.2016.34.5.19.

5. Kang M, Kim C. A review of joining processes for high strength 7xxx series aluminum alloys. *J Weld Join*. 2017;35(6):79-88. doi:10.5781/jwj.2017.35.6.12.
6. Musfirah AH, Jaharah AG. Magnesium and aluminum alloys in the automotive industry. *J Appl Sci Res*. 2012;8(9):4865–4875.
7. Miller WS, Zhuang L, Bottema J, Wittebrood AJ, De Smet P, Haszler A, et al. Recent development in aluminum alloys for the automotive industry. *Mater Sci Eng A*. 2000;280(1):37–49. doi:10.1016/S0921-5093(99)00653-X.
8. Qiu R, Iwamoto C, Satonaka S. Interfacial microstructure and strength of steel/aluminum alloy joints welded by resistance spot welding with cover plate. *J Mater Process Technol*. 2009;209(8):4186–4193.
9. Alizadeh-Sh M, Marashi S, Pouranvari M. Resistance spot welding of AISI 430 ferritic stainless steel: phase transformations and mechanical properties. *Mater Des*. 2014;56:258–263.
10. Dancette S, Fabrègue D, Massardier V, Merlin J, Dupuy T, Bouzekri M. Experimental and modeling investigation of the failure resistance of advanced high strength steels spot welds. *Eng Fract Mech*. 2011;78(10):2259–2272.
11. Zhang H, Qiu X, Xing F, Bai J, Chen J. Failure analysis of dissimilar thickness resistance spot welded joints in dual-phase steels during tensile shear test. *Mater Des*. 2014;55:366–372.
12. Sun M, Niknejad ST, Zhang G, Lee MK, Wu L, Zhou Y. Microstructure and mechanical properties of resistance spot welded AZ31/AA5754 using a nickel interlayer. *Mater Des*. 2015;87:905–913.
13. Zhang W, Sun D, Han L, Li Y. Optimised design of electrode morphology for novel dissimilar resistance spot welding of aluminum alloy and galvanised high strength steel. *Mater Des*. 2015;85:461–470.
14. Lu Y, Mayton E, Song H, Kimchi M, Zhang W. Dissimilar metal joining of aluminum to steel by ultrasonic plus resistance spot welding—microstructure and mechanical properties. *Mater Des*. 2019;165:107585.
15. Arghavani MR, Movahedi M, Kokabi AH. Role of zinc layer in resistance spot welding of aluminum to steel. *Mater Des*. 2016;102:106–114.
16. Hendrawan MA, Purboputro PI, Prima A. Use of zinc powder on resistance spot welding on mild steel and aluminum. In: *Journal of Physics: Conference Series*. 2021 Apr;1858(1):012051. IOP Publishing.
17. Wan Z, Wang HP, Chen N, Wang M, Carlson BE. Characterization of intermetallic compound at the interfaces of Al-steel resistance spot welds. *J Mater Process Technol*. 2017;242:12–23.
18. Qiu R, Iwamoto C, Satonaka S. Interfacial microstructure and strength of steel/aluminum alloy joints welded by resistance spot welding with cover plate. *J Mater Process Technol*. 2009;209(8):4186–4193.
19. Chen N, Wang HP, Carlson BE, Sigler DR, Wang M. Fracture mechanisms of Al/steel resistance spot welds in lap shear test. *J Mater Process Technol*. 2017;243:347–354.
20. Chen J, Yuan X, Hu Z, Li T, Wu K, Li C. Improvement of resistance spot welded joints for DP 600 steel and A5052 aluminum alloy with Zn slice interlayer. *J Manuf Process*. 2017;30:396–405.
21. Shi L, Kang J, Chen X, Haselhuhn AS, Sigler DR, Carlson BE. Determination of fracture modes in novel aluminum-steel dissimilar resistance spot welds. *Procedia Struct Integr*. 2019;17:355-362.
22. Al-Filfily AA, Al-Adili AS, Sar MH. Strength of resistance spot welding of aluminum alloy AA6061 to carbon steel using different filler materials. In: *IOP Conference Series: Materials Science and Engineering*. 2020 Jul;881(1):012067. IOP Publishing.
23. Hu S, Haselhuhn AS, Ma Y, Li Y, Carlson BE, Lin Z. Comparison of the resistance spot weldability of AA5754 and AA6022 aluminum to steels. *Weld J*. 2020;99(8):224S-238S.
24. Kang J, Shi L, Shalchi-Amirkhiz B, Sigler DR, Haselhuhn AS, Carlson BE. Microstructure and shear strength of novel aluminum to steel resistance spot welds. *Weld J*. 2020;99:67-s.
25. Kapil A, Mao Y, Vivek A, Cooper R, Hetrick E, Daehn G. A new approach for dissimilar aluminum-steel impact spot welding using vaporizing foil actuators. *J Manuf Process*. 2020;58:279-288.
26. Liu F, Hou Q, Hu H, Ma Y, Ning S, Wu Y. Study on microstructure and properties of resistance spot welding of Mg/Ti dissimilar materials. *Sci Technol Weld Joining*. 2020;25(7):581-588.

27. Shi L, Kang J, Gesing M, Chen X, Haselhuhn AS, Carlson BE. Effect of notch root angle on fatigue behavior of aluminum to steel resistance spot welds. *Int J Fatigue*. 2020;141:105866.
28. Mishra D, Rajanikanth K, Shunmugasundaram M, Kumar AP, Maneiah D. Dissimilar resistance spot welding of mild steel and stainless steel metal sheets for optimum weld nugget size. *Mater Today Proc*. 2021;46:919-924.
29. Chen J, Yuan X, Hu Z, Sun C, Zhang Y, Zhang Y. Microstructure and mechanical properties of resistance spot welded joints for A5052 aluminum alloy and DP 600 steel. *Mater Charact*. 2016;120:45-52.
30. Chen L, Zhang Y, Xue X, Wang B, Yang J, Zhang Z, Tyrer N, et al. Investigation on shearing strength of resistance spot welded joints of dissimilar steel plates with varying welding current and time. *J Mater Res Technol*. 2022;16:1021-1028.
31. Oliveira JP, Ponder K, Brizes E, Abke T, Edwards P, Ramirez AJ. Combining resistance spot welding and friction element welding for dissimilar joining of aluminum to high strength steels. *J Mater Process Technol*. 2019;273:116192.
32. Shi L, Xue J, Kang J, Haselhuhn AS, Carlson BE. Effect of specimen configuration and notch root angle on fatigue behavior of novel dissimilar resistance spot welds of AA5754 to HSLA steel. *Procedia Struct Integr*. 2022;37:351-358.
33. Guzanová A, Brezinová J, Varga J, Džupon M, Vojtko M, Janoško E, Viňáš J, Draganovská D, Hašul' J. Experimental study of steel–aluminum joints made by RSW with insert element and adhesive bonding. *Materials*. 2023;16(2):864.
34. Liu H, Zhu Y, Tian Y, Wei F, Zhou Y, Zhu Z. Study on mechanical properties and failure mechanism of medium manganese TRIP steel/DP590 dissimilar steel resistance spot welding joint. *Mater Res*. 2023;26.
35. Manladan SM, Ramesh S, Luo Z. Lap-shear performance of aluminum alloy 5754 and 420 martensitic stainless steel resistance spot weld. In: *AIP Conference Proceedings*. 2023 Jan;2643(1):050010. AIP Publishing LLC.
36. Qiu R, Li J, Shi H, Yu H. Characterization of resistance spot welded joints between aluminum alloy and mild steel with composite electrodes. *J Mater Res Technol*. 2023;24:1190–1202.
37. Shi L, Xue J, Kang J, Amirkhiz BS, Haselhuhn AS, Carlson BE. Tensile and fatigue behaviour of novel dissimilar resistance spot welds of AA5754 to steels: interplay of intermetallic layer, weld nugget diameter and notch root angle. *J Mater Res Technol*. 2023;22:1737–1752.
38. Winnicki M, Małachowska A, Korzeniowski M, Jasiorski M, Baszczuk A. Aluminum to steel resistance spot welding with cold sprayed interlayer. *Surf Eng*. 2018;34(3):235–242.
39. Chen N, Wang HP, Carlson BE, Sigler DR, Wang M. Fracture mechanisms of Al/steel resistance spot welds in coach peel and cross tension testing. *J Mater Process Technol*. 2018;252:348–361.
40. Chen J, Feng Z, Wang HP, Carlson BE, Brown T, Sigler D. Multi-scale mechanical modeling of Al-steel resistance spot welds. *Mater Sci Eng A*. 2018;735:145–153.
41. Ibrahim I, Ito R, Kakiuchi T, Uematsu Y, Yun K, Matsuda C. Fatigue behaviour of Al/steel dissimilar resistance spot welds fabricated using Al–Mg interlayer. *Sci Technol Weld Joining*. 2016;21(3):223–233.
42. Penner P, Liu L, Gerlich A, Zhou Y. Dissimilar resistance spot welding of aluminum to magnesium with Zn-coated steel interlayers. *Weld J*. 2014;93(6):225s–231s.
43. Wan Z, Wang HP, Wang M, Carlson BE, Sigler DR. Numerical simulation of resistance spot welding of Al to zinc-coated steel with improved representation of contact interactions. *Int J Heat Mass Transfer*. 2016;101:749–763.
44. Sun D, Zhang Y, Liu Y, Gu X, Li H. Microstructures and mechanical properties of resistance spot welded joints of 16Mn steel and 6063-T6 aluminum alloy with different electrodes. *Mater Des*. 2016;109:596–608.
45. Sun M, Niknejad ST, Gao H, Wu L, Zhou Y. Mechanical properties of dissimilar resistance spot welds of aluminum to magnesium with Sn-coated steel interlayer. *Mater Des*. 2016;91:331–339.
46. Sun M, Niknejad ST, Gao H, Wu L, Zhou Y. Mechanical properties of dissimilar resistance spot welds of aluminum to magnesium with Sn-coated steel interlayer. *Mater Des*. 2016;91:331–339.

47. Hu, S., Haselhuhn, A.S., Ma, Y., Li, Y., Carlson, B.E. and Lin, Z., 2021. Sensitivity of dissimilar aluminum to steel resistance spot welds to weld gun deflection. *J Manuf Process.* 68, pp.534–545.
48. Hayat F. The effects of the welding current on heat input, nugget geometry, and the mechanical and fractural properties of resistance spot welding on Mg/Al dissimilar materials. *Mater Des.* 2011;32(4):2476–2484.
49. Li Y, Zhang Y, Bi J, Luo Z. Impact of electromagnetic stirring upon weld quality of Al/Ti dissimilar materials resistance spot welding. *Mater Des.* 2015;83:577–586.