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A Review on Resistance Spot Welding of Steel Material

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Abstract:

The resistance spot welding is an efficient welding method. However, the resulted joints are affected by some parameters such as welding current, welding time, and electrode force. The effect of welding parameters on the mechanical properties and failure mode is reviewed in this study. The relationship between the joint strength and welding parameters is presented. The nugget diameterand metallurgy, loading and micro hardness were the target points to be evaluated in this study. The effect of annealing heat treatment on the weldment properties was investigated as well. Few of investigations studied the defect formation in spot weld. The most critical defects such as cracks and cavities are presented as well as the residual. Besides, the effect of welding environments on the joint properties is reviewed in this study. Dissimilar joining of aluminum and steel by using resistance spot welding represents a critical aim in vehicle manufacturing, it is a key challenge for multi-materials lightweight design strategy, and therefore, many investigations studied the dissimilar joining via RSW.

Keywords **—Resistance spot welding, Joint strength, Dissimilar joining, Aluminum and Steel.**

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I. INTRODUCTION

Resistance spot welding (RSW) is the process of joining two or three metal sheets via fusion at discrete spots at the sheets interface. It is widely used in many industrial sections such as aviation and transport applications (Fig 1). Fusion occurs according to heat generated from resistance to flow of the current through metal sheets [1, 2]. Temperature rises at the faying surfaces until reaching the plastic point of the metal, at high temperature the metal begins to fuse and a nugget will form. Then the current is switched off and weld nugget is allowed to cool down slowly until solidifying under pressure, (as shown in Fig 2). This process is completed within a short period; it may not exceeding parts of the second [3]. Professor Elihu Thomson invented the RSW process in 1877, and since then it has been extensively used in the manufacturing industries for joining metal sheets [4]. Many papers deal with the spot welding process and its variables in different subjects and fields.

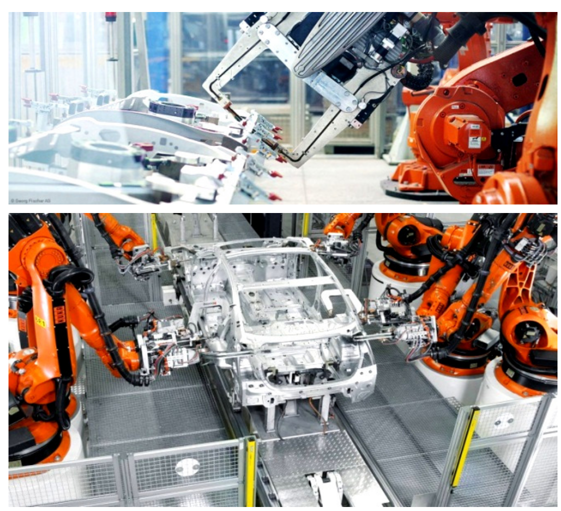


Fig. 1 Resistance spot welding processes [1].

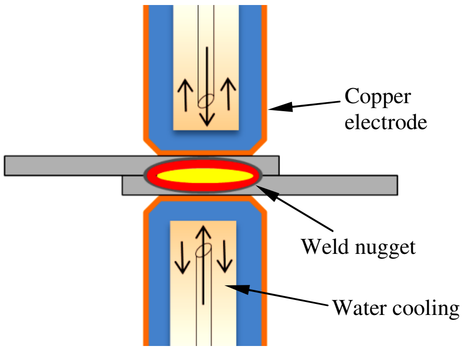


Fig. 2 A schematic of (RSW) process.

II. RESEARCH QUESTIONS

The following guided research questions of this study are to help the peer-review process. The questions are:

1. Is the steel joint made by RSW efficient and free of defect?
2. What are the hybrid sub-techniques that used in this type of joining?
3. What is the main feature of the resulted grain sizes distribution?
4. Is the annealing treatment affect the mechanical properties of weldments?

III. MATERIALS AND METHODS

The selected welded materials were limited to be low carbon steel, 304L austenitic stainless steel. However, the dissimilar Aluminum to steel was also reviewed in this study. The literature search was conducted on resistance spot welding of two sheets of selected materials. In general, the main procedure of the RSW explained in Fig 3

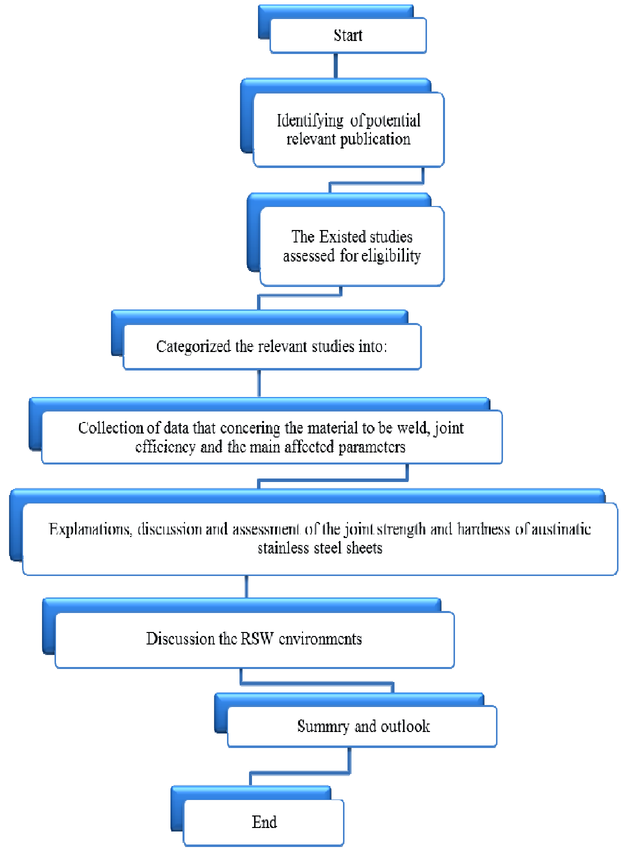


Fig.III Flow diagram of the study and process for studies inclusion.

IV. S]

With the present spot welding technique, it is practically impossible to avoid a certain number of defects, which include expulsion cracks and visible lack of fusion (shunting of current).

Few of investigations studied the defect formation in spot weld**.** The most critical defects like crack and cavity are presented in Ref. [5]. The cavitation's due to the welding parameters is shown in (Fig 4).

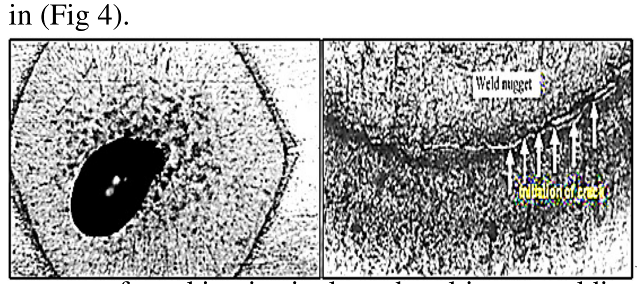
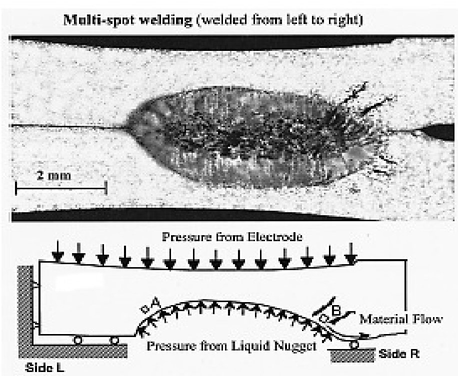
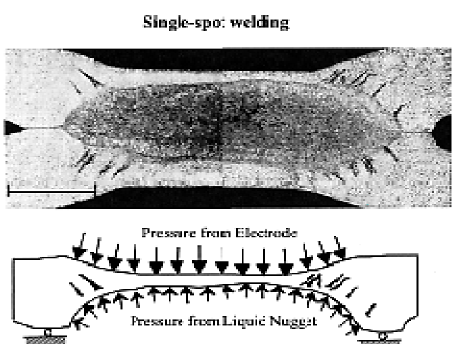


Fig.IV Cracking and cavitation's in weld nugget [5].

for AA5754 by both experimental and analytical approaches. They conducted the thermal-mechanical analysis based on the temperature distribution around the nugget (Fig 5) and the statement of stresses encountered during welding. They found that the cracking tendency is affected by various welding parameters and constraining conditions, such as welding electrode geometry, specimen geometry, welding sequence, and explosion. In addition, unlike fusion welding processes, constraining in resistance spot welding is preferred for minimizing cracking, because it reduces the tendency of generating tensile stresses in HAZ during welding. The electrode geometry should be carefully chosen. In most cases, the flat electrodes hinder cracking.



(A)



(B)

Fig.5 (A) Longitudinal cross-section of a multi-welded specimen. (B) A single welded specimen, with the representative loading and constraining conditions on half of the weldment locations [6].

Vl l
study on the fatigue strength of RSW for austenitic stainless steel 304 and galvanized steel sheets. The mode of resistance spot welding, which was used to join the sheet materials, was a lap joint. A nugget diameter and material combination had been selected as experimental parameters. The tests of high cycle fatigue had been performed and the S–N curves had been obtained for each specimen. The results show that sheets combination of galvanized steel has the highest fatigue limit. The combination of austenitic stainless steel 304 and galvanized steel sheets has the minimum fatigue limit. For the joint sheets of austenitic stainless steel–galvanized steel, the measurements of the crack length and nugget diameter were performed after fatigue tests. A crack growth rate of the spot welded austenitic stainless steel 304 and galvanized steel sheets was slow.

Mirsalehi and Kokabi 2010[8]**,** proposed an estimation approach for crack propagation-based fatigue life for resistance spot welds. The proposed approach also had taken into account the effect of residual stresses. The approach provides an accurate and systematic prediction of the spot weld joints life with various dimensions and shapes. Experimental verification tests confirmed the validity of the calculations, and a good agreement was found between the experimental data and theoretical predictions.

V. RESIDUAL STRESSES AND HARDNESS

Residual stresses in spot welded joints play an important role in affecting the durability of the joint. Residual stress in structure for many engineering metals can reduce the load carrying capability or service life of the weld structure. Besides the metallurgical factors the variables of resistance spot welding process vary with hardness along the weld nugget [9].

Triyono et al 2010 [10] studied the residual stresses at the interface of spot welded dissimilar metals between carbon steel and austenitic steel. Carbon steel SS400 with thickness of 3.0 mm and 1.0 mm thick austenitic stainless steel SUS304 were joined in a lap joint by resistance spot weld (RSW). Residual stresses at the interface of spot welded similar metals 3.0 mm and 1.0 mm thick austenitic stainless steel SUS304 were also measured as a comparison (Fig 6). Neutron diffraction was used to determine the normal, radial and hoop residual stresses. Residual stresses, both on the side of carbon steel and stainless steel, either the normal, radial and hoop direction tend to compressive and vary depending on the distance from the nugget center. These stresses differ from the residual stresses at the interface of spot welded similar austenitic stainless steel that tend to tensile.

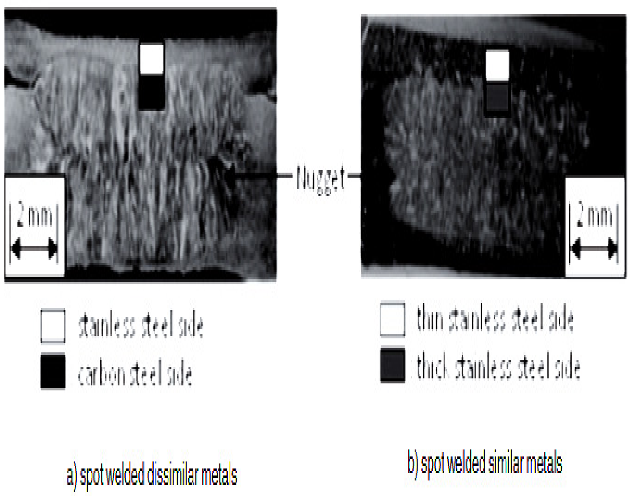


Fig. 6 Interface of spot welded similar and dissimilar metals [10].

VII. WELDING

For mass production process, e.g. automobile industry, the spot weldability of material is demanded. This is achieved by determination of the effective variable and the strength of weld nugget. Outline follows that may assist an operator in setting up and adjustment of machine setting to optimize the welding result [9].

A. *Effect of welding environments and welding time on the weldment hardness.*

N.Kahraman 2007 [11] studied the resistance spot welding of commercially pure titanium (CP) sheets. Different welding environments and different welding parameters were used. All welded joints had been subjected to tensile-shear tests to identify the strength of the welded joints. Microstructure and Microhardness examinations were carried out in order to study the effect of RSW parameters on the welded joints. All results indicate that increasing welding time and welding current increase the tensile-shear strength (Fig 7) and the welding under the argon atmosphere has given better tensile-shear strength. Microhardness distribution indicated that welding nugget had the highest values of hardness, followed by the HAZ and the base metal gave less values of hardness (Fig 8). Welding under the argon atmosphere had no effect on the hardness values. Microstructural examination showed that the deformations occurred in the welding zone during welding. The twinning occurred in the grains. The twinning would increase according to increase weld cycles and electrode force.

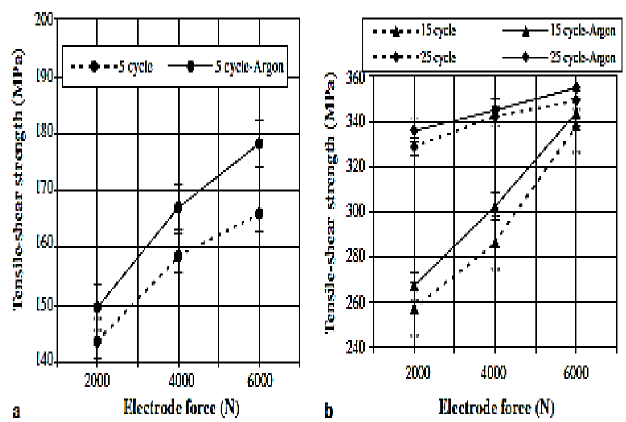


Fig. 7 Tensile-shearing test data: (a) 5 cycle weld time and (b) 15 and 25 cycle weld time [11].

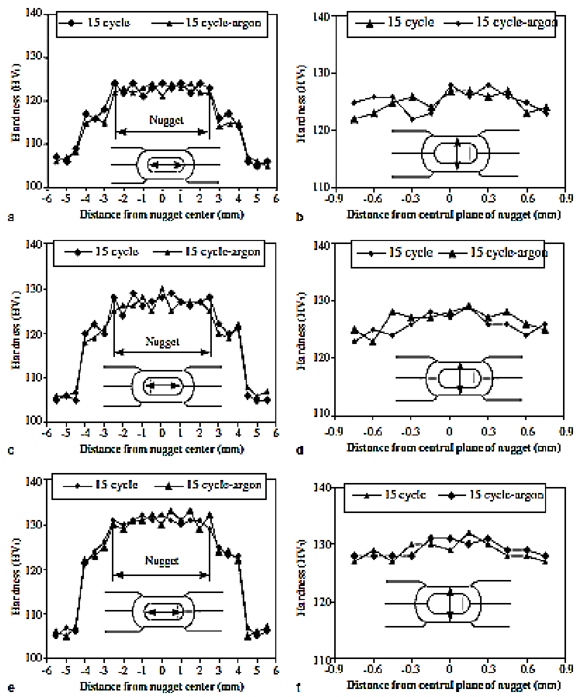


Fig.8Hardness of: (a) 2000 N, 15 cycle, (b) 2000 N, 15 cycle-Argon, (c) 4000 N, 15 cycle, (d) 4000 N, 15 cycle-Argon, (e) 6000 N, 15 cycle and (f) 6000 N, 15 cycle-Argon specimens welded at different parameters [11].

Dicknson and Natal 1987[12]investigated the effect of weld time on the hardness variation along the spot nugget of steel. They noticed that the hardness will randomly vary along the spot nugget, but the maximum hardness will be in heat affected zone, and secondly in the weld metal. It was demonstrated that the increase in weld time causes softening of the HAZ, but this increase would not change the hardness in the other regions as it does to those of HAZ.

B. *Spot Weldability and Effective Parameters*

Muna 1986[13], investigated the effect of resistance spot welding variables, such as welding current, welding time, electrode force and surface condition of the parts to be welded on the strength of spot welds of wrought heat-treatable aluminum alloys which are mainly used in aircraft construction. It was concluded that the increasing of the weld current and weld time and /or decrease electrode force, increasing the shear strength of spot-welds. Moreover, the results proved that has received surface condition, produced higher shear strength than in case of the surface cleaned by mechanical or chemical methods.

Al-Mukhtar 2002[9], studied the spot weldability of austenitic stainless steel (321) by studying the effect of welding variables on the mechanical properties of the weldments. The results showed that the weld joint strength and weld area were increased with increasing the weld current, weld time and electrode tip diameter. It was shown that the welding variables affected on the hardness of spot nugget. The heat treatment increased the softening through the compressive stress relief of the spot nugget.

Spot welding process like another welding process is affected by some variable and parameters, which determine the required heat generation for melting. Welding environment effects on the resistance spot weld quality.

N. Kahraman 2007 [10], studied the influence of welding parameters and welding under different welding environments on hardness of welded zones. Pure titanium sheets were welded by RSW under different welding environments and at different welding parameters. The results of hardness measurement indicate that the highest hardness has been given by welding nugget followed the HAZ and the lowest hardness distribution is at the base metal. The welding under argon gas has no influence on the hardness distribution.

J.B. Shamsul et.al 2007[14], investigated the relationship of welding current and nugget diameter . Microhardness distribution along weld nugget was also investigated. The material which was welded by RSW was austenitic stainless steel type 304. They performed the welding process under welding current which was changed from 2.50, 3.75, 5.00 and 6.25 Kamp. The results indicate that a large nugget diameter is obtained by increasing welding current, while increasing the welding current has no effect on the hardness distribution.

D. Özyürek 2008[15]**,** investigated the effect of main parameter affecting the heat input which is weld current, on the weld nugget size, surface appearances, weld internal discontinuities, weld penetration. The investigation material was austenitic stainless steel 304L. The welding currents were 4, 7 and 9 Kamp. Strength and ductility were determined for spot welded joints. He also studied the effect of weld atmosphere, which was atmosphere and nitrogen on the quality of resistance spot weld. Microhardness, microstructure, and tensile-shear strength of welded joints were determined for all conditions. The results indicate that the tensile-shear strength of welded joints increases with increasing heat input related with weld current due to the enlargement of nugget size. An optimum weld quality was obtained at welding current value of 9 Kamp. And in nitrogen atmosphere, see (Fig 9 and 10).

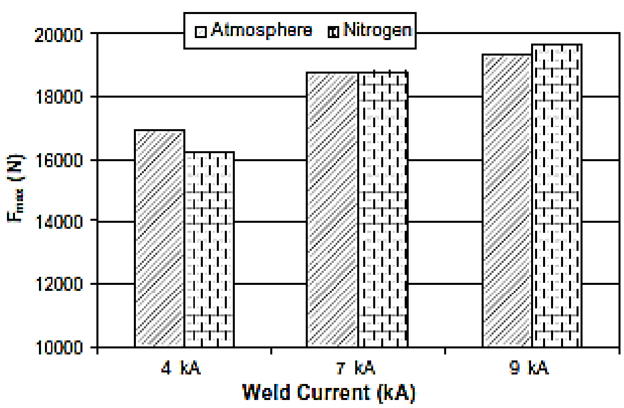


Fig. 9Tensile shear load bearing capacity resistance of spot welded samples cooled in atmosphere [15].

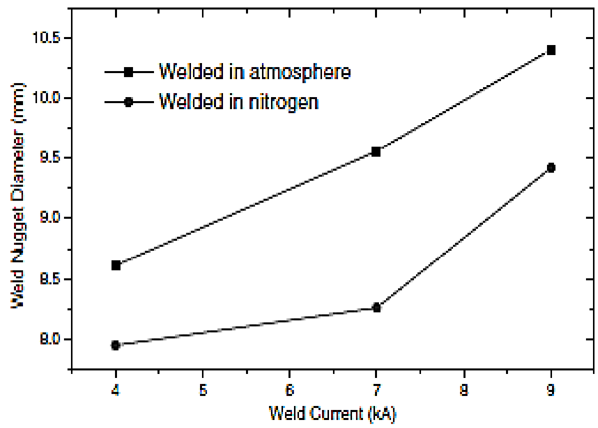


Fig. 10 Variation in the weld nugget size related with different weld current [15].

S. Aslanlar et.al 2007[16]**,** investigated the effect of welding time on the mechanical properties of lap-joint and curved peel-joint of galvanized chromate steel sheets with thicknesses 1.2 mm which welded in electrical RSW. An electrical RSW machine of 120 kVA capacity and equipped with a pneumatic application mechanism of a single lever used to prepare the specimens. Welding periods and welding currents were selected as 5, 10, 12 and 15 cycles and 4, 5, 6, 7, 8, 9, 10, 11 and 12 Kamp., respectively, and the electrode pressure was fixed at 6 KN. The welding joints were tested by tensile-shear and tensile-peel tests. They used related period diagrams to study the effect of welding time on tensile- shear and tensile - peel strength. Optimum welding times were obtained. The results indicate that the maximum tensile-shear strength is obtained at welding current of 10 Kamp. and welding time of 15 cycles, while the maximum tensile-peel strength is obtained at welding current of 11Kamp, And welding time of 10 cycles.

M. Pouranvari 2011[17] studied the effect of resistance spot welding variables (welding current, holding time, welding time, and electrode pressure) on performance of low carbon steel joints . A peak load, the maximum energy and failure mode obtained in tensile-shear test have been used to describe the performance of spot welds. Increasing the electrode pressure can reduce both maximum energy and peak load, considerably. Change in holding time did not have effect on maximum energy and peak load investigated material. Increasing welding current and welding time increases both maximum energy and peak load to some extent. However, excessive welding current and welding time, not only do not increase peak load and weld nugget size, but also cause decreasing maximum energy**.**

*Al-Mukhtar*2013 [5] published study dealing with spot weldment of 0.8mm carbon steel. The strips of lap joints and curved peel joints configurations have been welded traditionally, the welding current has a major effect on the weld area and joint strength more than the weld time and electrode pressure. If the current is low, the weld joint will have insufficient strength due to the brittleness nature of the produced nugget. A good correlation was obtained between tensile shear strength and weld nugget area. It finds that the weld strength proportion to the diameter of fused zones (weld nugget). The spot joint configuration has an effect on the heat dissipation. Therefore, the overlapped peel specimens have a higher nugget area, due to lower heat dissipation (higher heat built up) at nugget regions.

C. ***Optimization resistance welding parameters***

R. Manoj, and A. Vishal, (2014) [18]investigated of the effect and optimized of welding parameters on the tensile shear strength in the Resistance Spot Welding (RSW) process. The experimental studies were conducted under varying electrode forces, welding currents, and welding times. The settings of welding parameters were determined by using the Taguchi experimental design of L18 Orthogonal array method. The combination of the optimum welding parameters have determined by using the analysis of Signal-to-Noise (S/N) ratio. The confirmation test performed clearly shows that it is possible to increase the tensile shear strength of the joint by the combination of the suitable welding parameters. Hence, the experimental results confirmed the validity of the used Taguchi method for enhancing the welding performance and optimizing the welding parameters in resistance spot welding operations.

Vignesh et al 2017 [19] studied the effect of various control parameters like electrode tip diameter, welding current, and heating cycle on the nugget size and tensile shear strength of dissimilar metal spot welding of 2-mm-thick AISI 316L austenitic stainless steel and 2205 Duplex Stainless Steel sheets. The Taguchi's L27 orthogonal array (OA) design is selected to conduct the experimental spot welding trials on the dissimilar materials. Subsequently, the specimens are examined using analysis of variance (ANOVA) technique to customize optimal parameter setting to obtain high tensile strength and favorable weld quality characteristics. The results reveal that welding current is the most dictating factor to achieve highest tensile strength with superior weld quality. Also, weld samples are prepared for metallographic examination from cross section areas of resistance spot welds to examine microstructure changes and ferrite content measurement in different regions of weld nugget. The microstructure examination shows that the weld nugget consists of ferrite and austenite and ferrite and there is no precipitate of detrimental phases in the weldment.

VIII. TAGUCHI METHOD FOR OPTIMIZATION

Optimization of RSW parameters is the way to achieve high quality without increasing cost [20]. Optimization is performed by many methods; one of them is Taguchi method. Taguchi experimental method is a straightforward and easy to apply for many situations of engineering. It is a powerful and simple tool. It can be used to narrow the scope of a research project or to determine problems in the manufacturing process from data that are already in existence [20].

When the number of process parameters increases, a large number of experiments have to be carried out. To identify and reduce number of experiments, the Taguchi method uses a special design of orthogonal arrays to study the entire spaceof process parameters with a small number of experiments [21].

Thakur and Nandedkar 2014 [20], investigated the effect of welding parameters on the joint strength of weldments in the resistance spot welding process and optimized the RSW parameters. The experimental studies were carried out under varying welding currents, electrode forces, welding times, and electrode diameters. The welding parameters settings were determined using the Taguchi experimental design method. Determination of the level of importance of RSW parameters on the tensile shear strength was by using the (ANOVA). The optimum RSW parameter combination was obtained by using the (S/N) ratio. The confirmation tests explained that by using the Taguchi method it is possible to increase the tensile-shear strength significantly. The experimental results confirm the validity of the used Taguchi method to enhance the RSW performance and optimizing the welding parameters in the RSW process.

Thakur et.al 2010 [22], presented an experimental investigation on optimization of the Tensile-Shear strength of RSW for Galvanized steel by using used Taguchi method. Resistance spot welding of galvanized steel is always difficult because of tendency of zinc coating alloy with electrode. The experimental studies were carried out under varying weld currents, weld times, electrode force and electrode diameter. Orthogonal array of L27 has been used in order to determine signal to noise(S/N) ratio and analysis of variance (ANOVA), in addition, the F test value has been used for determining most significant parameters affecting the RSW performance. The results, based on the (ANOVA) method , show that the most effective parameters on tensile-shear strength are weld current and weld time, while electrode diameter and electrode force are less effective parameters. The results show that welding current has more importance and effect on the tensile shear strength than the weld time. The effect of weld current was about two times more than the effect of weld time. An optimum parameter combination, to maximize tensile shear strength, was obtained via using the analysis of the signal to noise (S/N) ratio. The confirmation tests show that it is possible to increase the tensile-shear strength (13.43 %) by using the statistical technique. The experimental results confirmed the validity of the Taguchi method to enhance the RSW performance and optimizing the RSW parameter.

IX. FAILURE MODES OF FRACTURE WELDMENTS

Failure of spot welds may affect the vehicle's stiffness and noise, vibration, and hardness (VH) performance on a global level. Therefore, the failure characteristics of spot welds are very important issue for the automotive industry [23]. Failure mode of resistance spot welds (RSWs) is a qualitative measure of mechanical properties. (Fig 11) shows the schematic representation of the main fracture mode during mechanical testing of the spot welds. Spot welds can fail in two distinct modes described as shown below:

1. Interfacial failure (IF) mode: in which the fracture proliferates through the fusion zone (FZ), (see Fig 11 a). This failure mode has a detrimental effect on the crash worthiness of the vehicles [24].
2. Pullout failure (PF) mode: it occurs by drawl of the weld nugget from one of two joint sheets. In pullout failure mode, fracture may get started in the base metal (BM), heat-affected zone (HAZ) (Fig 12), or HAZ /fusion zone, that depends on the geometrical and metallurgical characteristics of the weld zone and depends on the loading conditions [25], (see figure 11b). Generally, the pullout failure mode exhibits the very satisfactory mechanical properties.

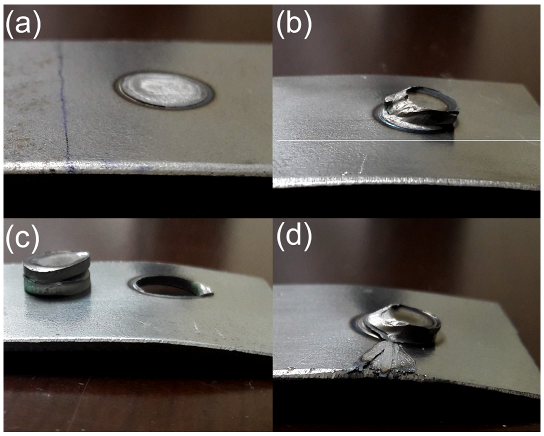


Fig.11Failure modes: a) interfacial, b) partial interfacial, c) complete bottom separation, d) partial pullout [25].

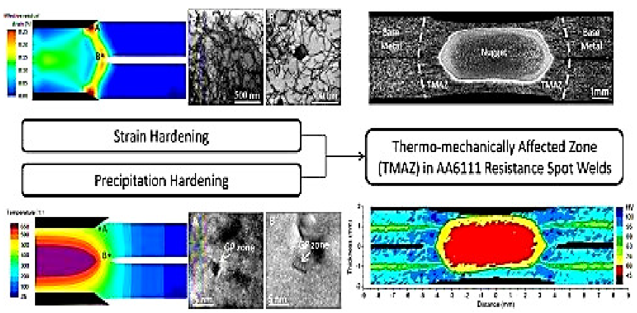


Fig.15 Heat affected zone (HAZ) [26].

Failure mode under which RSWs joints failure is an indicator of their energy absorption capability and load-bearing capacity. Failure spot weld in the nugget pullout mode provides high levels of energy absorption and peak loads than welded joints compared with the results obtained from the interfacial fracture mode [25]. Process parameters should be adjusted to ensure reliability of spot welds during lifetime of vehicle, for this reason the pullout failure mode should be guaranteed. The transition from Interfacial failure mode to pullout failure mode is generally related to the increase in size of the fusion zone above a minimum value. The minimum fusion zone size is a function of the sheet thickness, BM/HAZ/FZ material properties, and loading conditions [27]. Due to its significant impact on joint reliability, the failure mode is an important issue for some recent studies:

Pouranvari et.al 2009[28] studied behavior of resistance spot welded joint under coach-peel and tensile shear loading condition. The failure modes of RSWs, interfacial and pullout mode, were investigated depending on experimental observation. The optical micrographs of cross sections of spot welds in coach peel and shear-tensile specimens were examined to understand mechanism of the failure. The specimens had been examined by the optical micrographs before and after failure. Results show that to ensure pullout failure mode there is a critical size for fusion zone. The experimental results indicate that in the pullout failure mode during tensile-shear test, necking is started in weld nugget circumference in base metal and then the failure spreads along the weld nugget circumference in the sheets to final fracture. While during coach peel test the pullout failure occurred by initiation and propagation crack near the boundary between weld nugget and HAZ The critical fusion zone size which was required to ensure the pullout failure mode during the tensile shear test was larger than that which was required during coach-peel test [27].

Pouranvari and Ranjbarnoodeh 2011[29], dealt with the failure mode of DP600 dual phase steel resistance spot welds during quasi-static . It was found that the failure mode was altered from interfacial to pullout failure mode due to the increasing of welding current. Results showed that the conventional recommendation of $4t^{0.5}$ (where t is sheet thickness) for weld sizing is not enough to obtain the pullout failure mode during tensile-shear test of DP resistance spot welds. The minimum required fusion zone size to obtain pullout failure mode was estimated using an analytical mode.Increasing weld current leads to alter failure mode from the interfacial to the pullout failure mode.

Alemius et.al 2006 [23], determined the resistance spot welding parameters for the joints of dissimilar metals and characterization of the mechanical properties of the joints. Lap shear tests, cross-tension tests, peel tests, metallographic investigations, micro hardness measurements were performed.

They found that in dissimilar metal joints between stainless steel and no stainless steel, the failure load of the cross-tension specimens is less than that of the lap shear specimens by around 28%.

The weld nugget of the dissimilar metal joints was fully martensitic, which is ductile enough so that the failure mode was plug failure in both cross-tension and lap shear tests.

X. IMPROVE THE TENSILE SHEAR STRENGTH OF RESISTANCE SPOT WELDMENT

Al-Mukhtar et al 2018[30] have shown that the annealing improves the mechanical properties. Mechanical properties and quality of spot weldments improve by increasing the welding current. Residual stresses are induced in the spot weld area due to a large amount of heating in short time is induced in a sheet metal. Post weld heat treatment temperatures have been used. It was found that the annealing treatment refines the grain size and removes most of the residual stresses. So the strength will be improved up to annealing temperature of 750°C. The annealing temperature above 850 °C decreased the tensile shear strength. Because the transformation of the austenite grains gradually to Cementite gives more hardness and little elongation. In addition, the differences in solidification rates between compounds producing cracks. The shear strength increases with the increase of annealing temperature up (Table 1), (Fig 13).

TABLE 1: EFFECT OF ANNEALING ON THE TENSILE STRENGTH [30].

Current Amp.	Annealing Celsius	Shear strength (Mpa)
1000	Without annealing	137
	550 c°	144
	650 c°	149
	750 c°	151
	850 c°	130
2000	Without annealing	190
	550 c°	205
	650 c°	211
	750 c°	215
	850 c°	189
3000	Without annealing	202
	550 c°	207
	650 c°	214
	750 c°	218
	850 c°	200
4000	Without annealing	209
	550 c°	211
	650 c°	223
	750 c°	225
	850 c°	203
5000	Without annealing	223
	550 c°	230
	650 c°	233
	750 c°	235
	850 c°	218

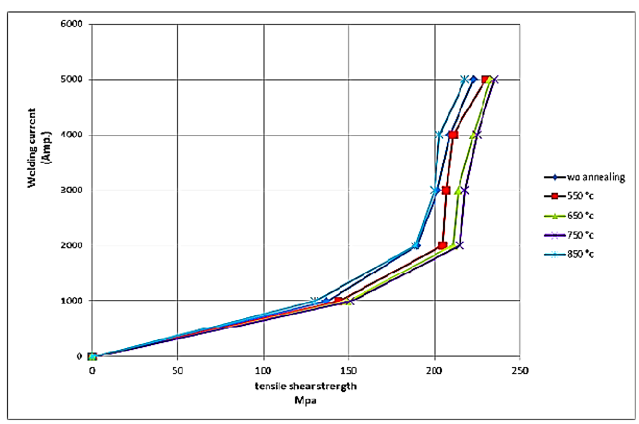


Fig. 13 Effect of annealing temperatures on the tensile shear stress [30].

XI. THE TRANSITION DISSIMILAR SHEETS

The transition or the intermediate metals are used to increase the surface resistance, hence increasing the weld nugget area. The bonding and the cracking are the main facts that determine the joint strength in this case.

Sun et.al 2004 [24], investigated whether resistance spot welding between steel and aluminum could be achieved by using a transition material. Experimental approaches were used to determine the optimal welding parameters and electrode combinations. Then nugget formation process had been examined using consecutive metallurgical cross-sectioning. They found that two distinct fusion zones are created during the RSW process of steel to aluminum by using a transition aluminum-clad steel strip. Weld nugget on the side of steel was an elliptical regular weld with dendritic grain structure inside the weld nugget region. The nugget on the side of aluminum was the top half of the elliptical shape. In addition, an intermetallic compound was formed on the aluminum/steel clad interface. This study demonstrated the spot weldability of steel to aluminum by using transition clad material and evaluated the structural performance of these welds. It should be mentioned that the cladding ratio of transition material, which was used in this study was not optimized. With using an optimized cladding ratio, it is envisaged that the joint strength, energy absorption, and failure mode of the dissimilar RSW population can be improved more. It should be noted that the economic and production feasibilities of introducing such transition welds into automotive production have to be studied. First of all, spot welding with insert of the transition material adds additional weight to the entire vehicle. Secondly, the relatively low yield of cladding process would increase the potential cost of the automotive industry. Moreover, the difference in the thermal expansion coefficients of the two cladding materials would promote the thermal distortion of the parts made of these materials. However, the results of this study actually suggest the potential application of aluminum clad steel as a load-bearing structural component as well as a material transition between the steel parts to the aluminum parts of the vehicle for optimized safety and weight reduction of a special vehicle design.

Hwang et.al 2007 [31], looked into the effect of the proportion of Mg in Al-Mg alloy on the mechanical properties and the interfacial microstructure of the joint. In addition, the effect of insert a thin sheet of commercially pure aluminum on the mechanical properties was studied. The obtained results indicate that the cross-tensile strength of the SS400 and Al-Mg alloy joint is remarkably low and less than 30% of that of the joint between SS400 and Al. However, the strength of (SS400/Al) joint was high and the fracture occurred in the aluminum base metal. A thick layer of intermetallic compound developed at the bonded interface of the (SS400/Al-Mg alloy) joint. Therefore, the joint strength decreased. The layer of intermetallic compound developed more thickly when the content of Mg in the Al-Mg alloy increased. Insert commercially pure aluminum improved the joint strength of the SS400/Al-Mg alloy and the strength was equivalent to the strength of the base metal.

XII. DISSIMILAR ALUMINUM TO STEEL RSW

As mentioned, the RSW is the primary joining method in automotive sectors. The low-cost, high speed production and possibility of multi-materials welding at a same time are the key beneficial make this welding method as the main target. The efforts is in progress by automobile manufacturers to minimize vehicle weight without affect the vehicle toughness have led to an increment in high strength-to-weight-ratio in the automobile architecture. Dissimilar joining of aluminum and steel is the challenging for multi-materials lightweight design strategy. Therefore, using RSW as a critical process in vehicle manufacturing is important.

Majid Pouranvari 2017 [32] focused on the metallurgical challenges during aluminum to steel joining by RSW. The metallurgical transformations during dissimilar aluminum to steel RSW and their consequent on the joint failure behavior had been investigated. It is required to achieve sound, strong and reliable joints. Controlling the formation and growth of Al_5Fe_2 (Fig 16) intermetallic is the promoted undesired issue for producing high strength. This critical assessment arise the current understating regarding factors affecting the joint properties and approaches to control the interfacial reaction.

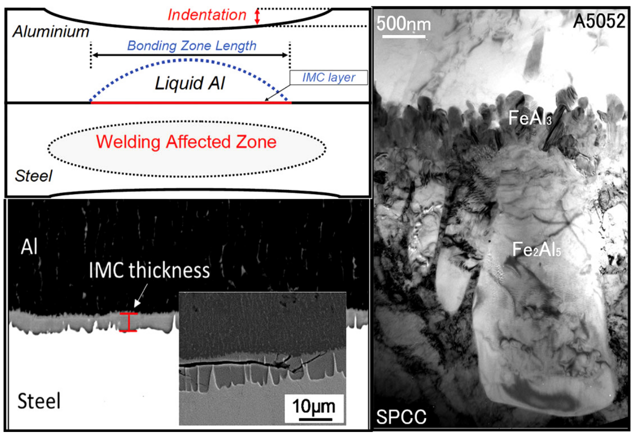


Fig. 16 Schematic of macrostructure dissimilar resistance spot welds between aluminum and steel [32]

XIII. CONCLUSION

From the current study and the reviewed result, the following conclusions can be obtained such as:

- Increasing the welding current and welding time result in the increment in tensile strength until expulsion of metal limit as a result of increasing weld nugget, while the electrode force has the opposite effect on the joint strength.
- The welding current parameter has the major effect on the joint strength. The time parameter has the second proportional effect according to joule law and to the experimental studies.
- Annealing treatment for steel could improves the joint strength.

The hardness value of the weld area increases with an increasing of the welding current and time.

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