

Research on Resistance Spot Welding of Stainless Steel - An Overview

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Abstract ---Resistance spot welding is an extensively used welding process for joining thin metal sheets in automobile, rail and aircraft industries. Research on resistance spot weldability of stainless steel attracts more and more attention with the increasing usage of various types of stainless steel in industries. In this paper, a review of research works done on resistance spot welding of stainless steel is presented. Most of the reported works on resistance spot welding of stainless steel have been on austenitic stainless steel, the most used variety of stainless steel. Though less, research works have been reported on other varieties of stainless steel also. The areas chosen for most of the works by researchers in the past have been found as process modelling and finite element analysis, dissimilar metal welding, failure mode analysis, parametric optimization and characterization of resistance spot welds. It is felt that the information presented in this report may definitely give the fresh researchers, a bird's eye view of the research work done in the past, in this field, and is expected to provide them the right direction for the future research work, in this area. The influence of three major areas such as mechanical, electrical and thermal coupled with the ever growing demand for stainless steel as a manufacturing material provides ample scope for fresh researchers for in depth studies in this field.

Key words--- Resistance spot welding, Stainless steel, Dissimilar metal welding, Optimization, Failure analysis, Mechanical properties, Microstructure.

1. INTRODUCTION

Resistance spot welding is widely used in sheet metal fabrication as an important metal joining process. It has got lot of applications in the field of automobile industries, rail coach manufacturing, aerospace and nuclear sectors, electric and electronic industries. It can be used on a variety of materials such as low carbon steel, nickel, aluminium, titanium, copper alloy, stainless steel and high strength low alloy steel [1]. It also plays an important role in Robotics [2]. Chao [3] stated that the modern vehicle contains 2000 to 5000 spot welds. Simplicity, low cost, high speed and automation possibility are among the advantages of this process [4].

Resistance spot welding was invented in 1877 by E. Thomson. It is a process of joining two or more metal parts by fusion at discreet spots at the interface of work pieces. Resistance to current flow through the metal work pieces and their interface generates heat and hence temperature rises at the interface of work pieces. When the melting point of the metal is reached, the metal will begin to fuse and a nugget begins to form. The current is then switched off and the nugget is cooled down to solidify under pressure [5, 6]. The amount of heat produced is a function of current, time, and resistance between the work pieces. Major factors

controlling this process are current, time, electrode force, contact resistance, property of the electrode material, sheet materials, surface condition etc [7].

Stainless steel is widely used in sheet metal fabrication, especially in automotive and rail coach manufacturing, mainly due to its excellent corrosion resistance and better strength to weight ratio. Stainless steel is a generic name covering a group of metallic alloys with chromium content in excess of 10.5 percent and a maximum carbon content of 1.2 percent (according to European Standard EN 10088) and often includes other elements, such as nickel and molybdenum. Due to formation of a passive layer, this is 1 to 2 nanometres thick; this metal exhibits excellent corrosion resistance. The passive layer is self healing, and therefore chemical or mechanical damages to it re-passivate in oxidizing environments [8, 9]. Stainless steel has been widely used for rail vehicle body shell design for many years owing to its corrosion resistance, low life-cycle cost, high strength-to-weight ratio and fire resistance [10].

2. RESISTANCE SPOT WELDING OF STAINLESS STEEL

Among the five categories of stainless steel, austenitic stainless steels are preferred materials for

structural application in railway carriages. They are already widely accepted for use in structural frameworks and body panelling of buses and coaches [11]. Stainless steels are spot weld able, some grades more readily than others. Austenitic grades of the 300 series are the most commonly welded types, followed by ferritic stainless steel. Martensitic stainless steels are the least common because welded joints are always much more brittle. Some studies have been reported on resistance spot welding on another variety of stainless steel precipitation hardened stainless steel such as 17-4 PH grade which has got wide applications in aerospace industries [12]. Much works have not been reported on resistance spot welding of duplex stainless steel which is another important and emerging type of stainless steel. Wray and Linder et al. have studied the fatigue performance of spot welded duplex stainless steels and they attempted to optimise the welding parameters (time, current and pressure) to achieve the best micro and macrostructures[13].

Stainless steels are excellent candidates for car body structural applications. Offering weight savings, enhanced “crashworthiness” and corrosion resistance, it can also be recycled. The material blends tough mechanical and fire-resistant properties with excellent manufacturability. Under impact, high-strength stainless offers excellent energy absorption in relation to strain rate [14].

With increasing demand for stainless steel in automotive and rail sectors, research works on resistance spot welding of stainless steel assumes a lot of significance. Most of the present guidelines and recommendations are for low carbon steel and there is limited information reported related to spot weldability of stainless steels. In this paper, an attempt is made to consolidate and highlight the results obtained by various researchers on spot welding of stainless steel in the past. Most of the research works reported on resistance spot welding of stainless steel can be broadly divided in to five groups. They are

1. Process modelling and Finite Element analysis
2. Dissimilar metal welding
3. Failure mode analysis
4. Parameter optimization
5. Characterization of RSW welds.

2.1 Process modelling and FE analysis

Many works have been reported on various aspects of modelling, simulation, and process optimization in the resistance spot welding process of stainless steel. In these works, detailed analysis has been made to establish relationships between welding parameters weld strength, weld quality, and productivity to select welding parameters leading to an optimal process.

A mathematical model can be utilized to analyze the resistance spot welding process and make use of the computational power of today's computers to employ complex mathematical formulations to simulate the welding process according to physical laws. Once verified, it can be used to explain the observed experimental phenomena, to provide insights into the local material response for selecting process parameters, and to minimize the amount of experimental work [15].

Significant time and money can be saved with the use of software that simulates the process of resistance welding. *Sorpas* is a software, used to assist design of resistance welding parts and joints. It determines welding parameters, how welding parameters can be optimized for various conditions in production, and forecasts the microstructure of the parts after welding [16].

Resistance spot welding process comprises of electric, thermal and mechanical phenomenon, which makes this process complex and highly non-linear and thus, it becomes difficult to model it. H A

Nied [15], developed an axi-symmetric finite element model to simulate this coupled process, using iso-parametric solid elements to represent the electrode and work piece, and boundary elements to represent surface contact conditions. The model was tested on AISI 321 grade austenitic stainless steel.

Martin et al.[17] developed a tool capable of reliably predicting the tensile shear load bearing capacity (TSLBC) in spot welding of AISI304 grade austenitic stainless steels. The said model was used for analyzing the squeeze and weld cycles to determine the electrical, thermal, and mechanical responses. Predictions of the temperature distribution, thermal expansion and associated stresses, and weld nugget geometry were obtained from this model.

C. L. Tsai et al.[18], attempted to model the resistance spot welding process and simulated it using the finite element code ANSYS. The mechanical behaviour of the process coupled with the transient thermal responses during spot welding was analyzed. The weld nugget formation in resistance spot welding of AISI 347 grade austenitic stainless steel of equal and unequal thicknesses and also of AISI 347 austenitic stainless steel to AISI 1045 carbon steel was studied. Finite element model took into account, mechanical behaviour as well as transient thermal responses of resistance spot welding.

Though not specific to stainless steel in particular, Thakur.A.G et al.[19], developed a 2D axi-symmetric FEM model to analyse the transient thermal behaviours of process using ANSYS software and coupled structural- thermo electric analysis was performed by using advanced coupled field element PLANE223 to simulate the thermal characteristics of resistance spot welding process in general. The objectives of this analysis were to understand physics of the process and to develop a predictive tool reducing the number of experiments for the optimization of welding parameters.

Y Zhang et al.[20] investigated the cooling rates at different areas of a spot welded nugget in a 1Cr18Ni9Ti stainless steel material, based on the rapid solidification theory and Furer-Wunderlin secondary dendrite arm spacing (SDAS) model. In the calculation of the cooling rates by using a SDAS method, only the diffusion of carbon atoms, which spread rapidly as a solute element in the solid phase, was considered. The experimental results showed that the SDAS values in a 1Cr18Ni9Ti spot welded nugget exhibited significant variation even for those on the same primary dendrite axis. The estimated cooling rate from the nugget edge to nugget centre decreased from an order of magnitude 10^5 to 10^4 Kelvin/sec.

2.2 Dissimilar metal welding

Dissimilar resistance spot welding can be more complex than similar welding due to different thermal cycle experienced with each metal.

Resistance spot welding of stainless steel with low alloy steels attracted the attention of many researchers, since dissimilar metal joints of stainless steel find a lot of applications in industries. Many studies have been reported on this area with different combinations with one of the material as stainless steel.

Murat et al.[21], have studied on the resistance spot weldability of galvanized interstitial free steel sheets with austenitic stainless steel sheets.

M. Alenius et al.[22] explored the mechanical properties of spot welded dissimilar joints for stainless and galvanized steels in a study made in 2006. Numerous tests were performed to determine the spot welding parameters for the dissimilar metal joints and to characterize their mechanical properties. Spot weld ability of dissimilar metal joints between stainless steels and non stainless steels was investigated in this work.

A. K. Biradar et al. [23] in the year 2009 made a study on resistance spot welding of dissimilar metal between mild steel and AISI 304 austenitic stainless steel, having medium range thickness. The spot welding of dissimilar metals of medium range thickness (0.8 mm to 1.2 mm M.S. and S.S. sheets) was carried out by varying the welding parameters such as welding time, welding current and welding force. A polynomial equation of first order to correlate weld strength with weld time, weld current and weld force was developed.

Mehdi Mansouri Hasan Abadi et al. [24] in the year 2010, studied about the correlation between macro/micro structure and mechanical properties of dissimilar resistance spot welds of AISI 304 austenitic stainless steel and AISI 1008 low carbon steel. Structure-properties relationships in dissimilar resistance spot welding of AISI 304 austenitic stainless steel (SS) and AISI 1008 low carbon steel (CS) were investigated.

Nachimani Charde [25] ,attempted to do characterization of spot weld growth on dissimilar joints with different thicknesses, using AISI 304 stainless steel and carbon steel. This paper focused on the effect of parametric changes for dissimilar joints using 304 austenitic stainless steel and carbon steel with two different thicknesses.

R.K Rajkumar et al. [26], investigated the Dissimilar Weld Joints of AISI 302 Austenitic Stainless Steel and Low Carbon Steel in a research work . This paper analyzes the spot weld growth on 302 austenitic stainless steel and low carbon steel of 1mm of thickness. They reported that the parametric changes (current and time) have resulted proportional changes in tensile strength regardless of base materials. They also reported that the fusion zones of carbon steel were found shorter than that of stainless steel but the heat affected zones were wider than the stainless steel.

A. Aravinthan et al. [27], made a study on dissimilar metal spot joint between stainless steel and mild steel ,focussing the nugget growth by

varying current and weld time . The tensile tests showed significant relationship between differing current increments and sufficient weld time to attain a proper weldment.

Nachimani Charde [28], analysed the effect of parametric changes for dissimilar joints using 304 austenitic stainless steel and carbon steel with two different thicknesses. He reported that hardness increments of welded side (from 55HRB to 100HRB and from 75HRB to 100HRB) do exist because of the heat treatment that happened during welding process.

Ladislav Kolarik et al. [29], investigated the properties of dissimilar resistance spot welds between low carbon steel and austenitic CrNi stainless steel. The thickness of the welded dissimilar materials was 2 mm. They reported that the HAZ(Heat affected zone) of the low carbon steel sheet had been found broader than the HAZ of the austenitic stainless steel. Grain refining of ferrite grains was observed in the low temperature HAZ at carbon steel. The hardness was found to be higher in the fusion zone.

2.3 Failure mode analysis

Generally, the resistance spot weld (RSW) failure occurs in two modes: interfacial and pullout. In the interfacial mode, failure occurs via crack propagation through fusion zone; while, in the pullout mode, failure occurs via complete (or partial) nugget withdrawal from one sheet. Spot weld failure mode is a qualitative measure of the weld quality. Spot welds that fail in nugget pullout mode provide higher peak loads and energy absorption levels than those which fail in interfacial failure mode. Generally, the pullout mode is the preferred failure mode due its higher associated plastic deformation and energy absorption

Chao YJ [3] in a study analysed the failure modes in resistance spot welding in general and presented a mathematical analysis to predict the failure mode, either nugget pullout or interfacial.

This analysis yielded a critical nugget diameter which distinguishes the two failure modes.

M. Pouranvari et al. [30], studied the behaviour of dissimilar resistance spot welded joints of low carbon and austenitic stainless steels, under tensile-shear test with attention focused on the failure mode. It was reported that in pullout failure mode, necking is initiated at nugget circumference and then the failure propagates along the nugget circumference in the sheet to final fracture. Necking location was low carbon steel side. Results showed that there is a critical fusion zone size to ensure pullout failure mode in shear tensile test, which is mainly controlled by ratio of fusion zone hardness and failure location hardness. In the case of dissimilar resistance spot welding, the hardness of the fusion zone which is governed by the dilution between two base metals, and fusion zone size of low carbon steel side are dominant factors in determining the failure mode of the joint

V.J. Badhekaa et al. [31], investigated mode of failure of resistance spot welded martensitic stainless steel. They concluded that faster cooling rate, higher carbon content, absence of post heating are responsible for cracking in the weld and subsequently interfacial failure.

M. Pouranvari [32], made a study regarding failure mode of AISI304 grade stainless steel resistance spot welds under quasi-static tensile-shear test. Results showed that the conventional weld size recommendation of $4\sqrt{t}$ is not sufficient to guarantee pullout failure mode for AISI304 stainless steel RSWs during tensile-shear test. Considering the failure location and failure mechanism in the tensile-shear test, minimum required fusion zone size to ensure the pullout failure mode was estimated using an analytical model. According to this model, in addition to sheet thickness, ratio of fusion zone hardness to failure location hardness is the key metallurgical factor governing failure mode of spot welds during the tensile shear test.

M Pouranvari et al. [33] studied the failure mechanism of resistance spot welds of AISI 304 stainless steel, during the cross-tension test with the aid of SEM investigation. They observed that fusion zone size and hardness characteristics are key factors controlling the failure mode of AISI 304 resistance spot welds. It was found that sheet thickness, fusion zone size, and hardness characteristics of the welds are key factors controlling the failure mode of spot weld. Results also showed that increasing the fusion zone size improved the peak load of spot welds in both cross-tension and tensile-shear tests.

Marius Chirileanu et al. [34], investigated the failure modes under tensile forces of the Resistance Spot Welding joints. The purpose of this work was to highlight the influences of joint materials and welding parameters on the tensile strength and on the failure mode of the joints.

The effect of a corrosive (3% NaCl aqueous) environment on the fatigue properties of spot welded AISI 304 and duplex SAF 2304 stainless steel is reported by Linder and Melander [13]

2.4 Optimization of parameters

A better quality weld is obtained by optimizing the process parameters because they play a vital role in deciding the weld strength. Optimization of parameters leads to the desired weld quality. Quality and strength of the spot welds are defined by the quality of the weld nuggets [35]. The quality of a resistance spot weld is best judged by the nugget size, heat affected zone (HAZ) and joint strength [36].

A. G. Thakur et al. [37], in a study in the year 2010, attempted to apply Taguchi method for optimization of tensile shear strength in resistance Spot Welding of stainless steel of grade AISI 304. It was reported that current is the most significant parameter influencing the tensile strength of the weld with a percentage contribution of

31.18%, followed by weld time with a percentage contribution of 17.77%.

Chinmoy Mondal et al.[38] attempted optimization of spot welding of 0.6 mm thick 17-4 precipitation hardening stainless steel by using the analytic hierarchy process and obtained good weld nuggets with a current of 2.5 KA, for a welding time of 6 to 7 cycles and also with another current value of 6 to 7 KA with a welding time of 5 cycles keeping load as constant at 4 KN.

T Wray attempted to optimise the welding parameters (time, current and pressure) of resistance spot welding of duplex stainless steel, to achieve the best micro- and macrostructures. Welding current was varied between 4.7 to 5 kA with 15 cycles for 2101 and SAF 2304, 20 cycles for 2205 and 25 cycles for SAF 2507. The electrode force was 3.25 kN. The nugget diameter was 4.5 to 4.9 mm [13]

2.5 Characterization of weld joint in RSW

J.B. Shamsul et al.[1] studied the relationship of nugget diameter and welding current in resistance spot welding of AISI 304 stainless steel. Hardness distribution along welding zone was also investigated. The results indicated that increasing welding current gave large nugget diameter. However, the welding current not much affected the hardness distribution. Also it was reported that nugget size does not influence the hardness distribution.

Bouyousfi et al.[39] , have studied the effect of process parameters (arc intensity, welding duration and applied load) on the mechanical characteristics of the weld joint of austenitic stainless steel 304L. The results showed that the applied load seems to be the control factor of the mechanical characteristics of weld joint compared to the welding duration and the current intensity

M. Pouranvari et al. [40], in an another study on resistance spot welding of stainless steel,

investigated the effect of welding current on the energy absorption capability of austenitic stainless steel AISI304 resistance spot welds during the quasi-static tensile-shear test . Results showed that there is a direct relationship between the fusion zone size and failure energy in expulsion free samples.

Nachimani Charde et al.[41], in a paper ,on investigation of spot weld growth on 304 austenitic stainless steel(2 mm) sheets ,reported that the growth of a spot weld is primarily determined by its parameters such as current, weld time, electrode tip and force. This paper is intended to analyze only the effects of nuggets growth due to the current and weld time increment with constant force and unchanged electrode tips. He reported that the hardness of welded zones is greater than the hardness of the un-welded zone and also the heat affected zones.

Welding Current Effect on Mechanical Properties of Spot Welded Dissimilar Metals between Stainless Steel and Low Carbon Steel was investigated by Agustinus Eko Budi Nusantara et al. [42] in the year 2011. It was reported that increasing of welding current had increased the nugget size and tensile-shear load bearing capacity of the joint. It also changed the interfacial failure to pull out failure.

Vural et al.[43], investigated the effect of welding nugget diameter on the fatigue strength of the resistance spot-welded joints of different steel sheets such as galvanized steel sheets and austenitic stainless steel.

Triyono et al.[44] made a comparative study on the fatigue strength of resistance spot-welded unequal and equal sheet thickness austenitic stainless steel grade AISI 304. Due to significant thickness difference, the asymmetric weld nugget, high micro hardness on the edge of nugget and tearing fatigue fracture mode were reported

3.CONCLUSION

In the foregoing sections, many of the research works carried out on resistance spot welding of stainless steel have been presented. Several aspects on process modelling, dissimilar welding, failure mode analysis, parameter optimization and characterization of weld joint have been highlighted. Some of the important results are mentioned below.

1. In general the hardness of the spot welded zone is greater than the hardness of the unwelded zone
2. In case of dissimilar joints, asymmetrical shape of weld nuggets is observed due to heat imbalance caused by difference in thermal conductivity and electrical resistivity.
3. Increasing welding current increases the nugget size in spot weld, however increasing welding current does not increase the hardness distribution.
4. Among the various spot welding parameters, welding current was found to be the most influential one determining the tensile strength.
5. There is a critical nugget diameter which distinguishes the two failure modes in spot welds-pullout failure mode and interfacial failure mode.
6. Tensile forces have proportional relationship with current and weld time increments until the expulsion limit occurs
7. The common three failure modes were seen as the poor weld produces an interfacial fracture (IF); the medium weld produces tear form one side (PF); and a good weld produces button pullout or tear from both sides (TF).
8. The welding current and weld time increments have resulted diameters increment at the welded zones.

9. Estimated cooling rate from the nugget edge to nugget centre decreased from an order of magnitude 10^5 to 10^4 Kelvin/sec.

It has been observed that, most of the research works done on spot welding of stainless steel are on austenitic stainless steel. With the other varieties of stainless steel also finding more and more applications in rail and automobile industries, more in depth studies of spot welding of those varieties on different aspects mentioned above, assumes a lot of significance.

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