Association of Metallurgical Engineers of Serbia
AMES

Scientific paper
UDC: 628.477:669.715

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

Mehdi Mansouri Hasan Abadi[1], Majid Pouranvari[2*]

[1]*Islamic Azad University, Najafabad Branch, Najfabad, Iran*
[2]*Islamic Azad University, Dezful Branch, Dezful, Iran*

Received 20.04.2010
Accepted 05.06.2010

Abstract

Structure-properties relationships in dissimilar resistance spot welding of AISI 304 austenitic stainless steel (SS) and AISI 1008 low carbon steel (CS) are investigated. Differences in physical and mechanical properties of both steel sheets affect resistance spot weldability of this combination. Weld nugget shape is asymmetrical and the final fusion line shifts from sheet/sheet interface into the higher resistivity side (i.e. AISI 304). Fusion zone microstructure was ranged from Ferrite-Austenite-Martensite to full martensite depending on the melting/dilution ratio of base metals. Criteria for selection optimum welding condition for dissimilar combination are discussed. It was shown that generally there is a direct relation between mechanical performance (peak load and failure energy) and FZ size of low carbon steel side. The peak load of CS/CS and SS/LCS was nearly same due to the fact that the pullout failure mode of SS/CS welds is initiated from CS base metal. However, the failure energy of the later was greater than the former weld which is a function of higher ductility of SS that helps increasing plastic deformation during process of pullout failure.

Key words: Resistance spot welding; Failure mode; Dissimilar metal joints

Introduction

Resistance spot welding (RSW) is considered as the dominant process for joining sheet metals in automotive industry. Typically, there are about 2000–5000 spot welds in a modern vehicle. Simplicity, low cost, high speed (low process time) and automation possibility are among the advantages of this process. Quality and mechanical behavior of spot welds significantly affect durability and crashworthiness of the vehicle [1]

---

[*] Corresponding author: Majid Pouranvari mpouranvari@yahoo.com

Resistance spot welding is a process of joining two or more metal parts by fusion at discrete spots at the interface of work pieces. Resistance to current flow through the metal work pieces and their interface generates heat; therefore, temperature rises at the interface of the 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 [2].

There are generally three indexes for quality control of resistance spot welds:

i) Fusion zone size (FZS): FZS which is defined as the width of the weld nugget at the sheet/sheet interface in the longitudinal direction is the most important factors in determining quality of spot welds.

ii) Weld mechanical performance

Spot weld mechanical performance is generally considered under static/quasi-static and fatigue loading condition. The tensile-shear test is the most widely used test for evaluating the spot weld mechanical behaviors in static condition [3]. Peak load, obtained from the tensile-shear load - displacement curve, is often used to describe spot welds mechanical behaviors. In addition to peak load, failure energy can be used to better describe the spot weld mechanical behaviors. Failure energy is a measure of weld energy absorption capability, and its higher value demonstrates the increase in weld performance reliability against impact loads such as accidents [4, 5].

iii) Failure mode

Failure mode is the manner which spot weld fails. Generally, the resistance spot weld (RSW) failure occurs in two modes: interfacial and pullout [6-8]. Fig.1 shows typical fracture path during mechanical testing of spot weld. In the interfacial mode, failure occurs via crack propagation through fusion zone (Path A); while, in the pullout mode, failure occurs via nugget withdrawal from one sheet. In this mode, fracture may initiate in BM (Path B), HAZ (Path C) or HAZ/FZ (Path D) depending on the base metal and the loading conditions.

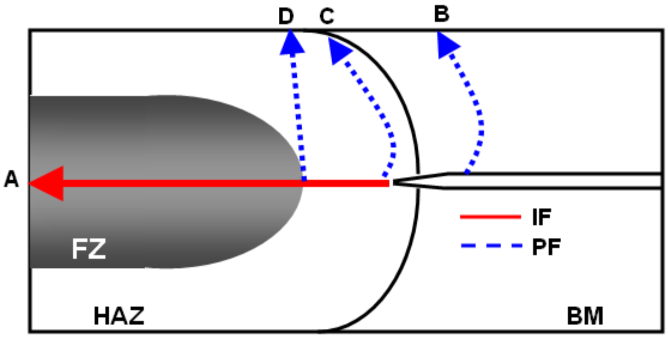


Fig.1 General fracture path during mechanical testing of resistance spot welds, IF: Interfacial Failure (Path A), PF: Pullout Failure (Path B, Path C and Path D)

Spot weld failure mode is a qualitative measure of the weld quality. Failure mode can significantly affect load bearing capacity and energy absorption capability of RSWs. Generally, the pullout mode is the preferred failure mode due its higher associated plastic deformation and energy absorption. Thus, vehicle crashworthiness, as the main concern in the automotive design, can dramatically reduce if spot welds fail via interfacial mode. The pullout failure mode during quality control indeed indicates that the same weld would have been able to transmit a high level of force, thus cause severe plastic deformation in its adjacent components, and increased strain energy dissipation in crash conditions [9]. Therefore, it is needed to adjust welding parameters so that the pullout failure mode is guaranteed.

The majority of the research investigations in spot welding have been carried out on the welding of similar sheets. However, in many applications, spot welds are made between different materials as mechanical properties are tailored to local requirements [10]. Despite various applications of dissimilar RSWs, reports in the literature dealing with their mechanical behaviors are limited. Resistance spot weldability diagrams and guidelines are almost for low carbon resistance spot welds. There are few documented data for spot welding of stainless steel. Dissimilar resistance spot welding of low carbon steel and austenitic stainless steels has been studied by some researchers [11-14]. Alenius et al. [11] studied weldability of various dissimilar metal joint between austenitic stainless steel and non-stainless steels. They concluded that the strength of the dissimilar joint in tensile-shear test is dictated by strength and thickness of non-stainless steels. Poggio et al. [14] studied spot welding behavior of Dissimilar DP600/304stainless steel joint.

The aim of the present paper is to investigate and analyze structure-properties relationships of dissimilar AISI 304/AISI 1008 resistance spot welds.

Experimental procedure

A 1.1 mm thick AISI 1008 galvanized low carbon steel (CS) and 1.2 mm thick AISI 304 austenitic stainless steel (SS) sheets were used as the base metals, in this research. The chemical composition of galvanized carbon steel (CS) and stainless steel (SS) is given in Table 1.

Table1. Chemical composition of test materials (%wt)

Element	C	Mn	Si	Cr	Ni	Mo
SS	0.035	1.08	0.388	18.47	9	0.561
CS	0.065	0.404	0.095	0.017	0.032	0.004

Spot welding was performed using a PLC controlled 120 kVA AC pedestal type resistance spot welding machine operating at 50 Hz. Welding was conducted using a 45-deg truncated cone RWMA Class 2 electrode with 7-mm face diameter. To dissimilar RSW of SS and CS, welding time and electrode force were kept constant at 12 cycles and 4.2 kN and welding current was varied step by step from 7 to 14 kA.

The tensile-shear test was used to explore mechanical properties of the joints. Fig.2 shows the sample dimensions. Samples were prepared following AWS standard [15]. Mechanical tests were performed at a cross head of 2 mm/min with an Instron universal testing machine. Peak load and failure energy (measured as the area under the load-displacement curve up to the peak load) were extracted from the load-displacement curve (see Fig.3). The Failure mode was determined from the failed samples.

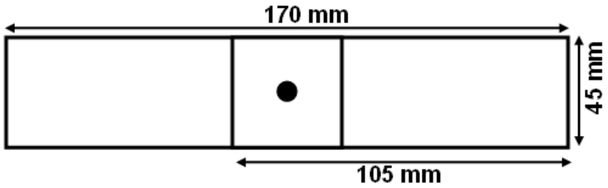


Fig.2 Sample dimensions of tensile-shear test

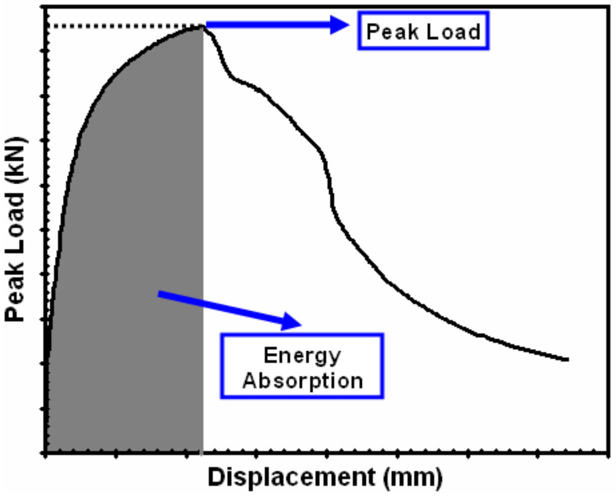


Fig.3 A typical load-displacement curve of spot welds during tensile-shear test

Samples for metallographic examination were prepared using standard metallography procedure. Optical microscopy was used to examine the microstructures of the joints. Fusion zone size of the spot welds was measured using optical microscope. Microhardness test was used to determine the hardness profile of the joints, using a 100g load on a Shimadzu microhardness tester. The microhardness traverses were performed on a diagonal covering microstructural zones in both sheets. The indentations were spaced 0.3 mm apart.

Results and discussion

Macro/Micro-struccture of dissimilar SS304/CS RSW

Fig.4 shows a typical macro/micro structure of a dissimilar resistance spot weld between low carbon steel (CS) and austenitic stainless steel (SS). As can be seen, the joint region consists of three distinct structural zones:

i) Fusion Zone (FZ) or weld nugget,
ii) Heat Affected Zone (HAZ), and
iii) Base Metal (BM).

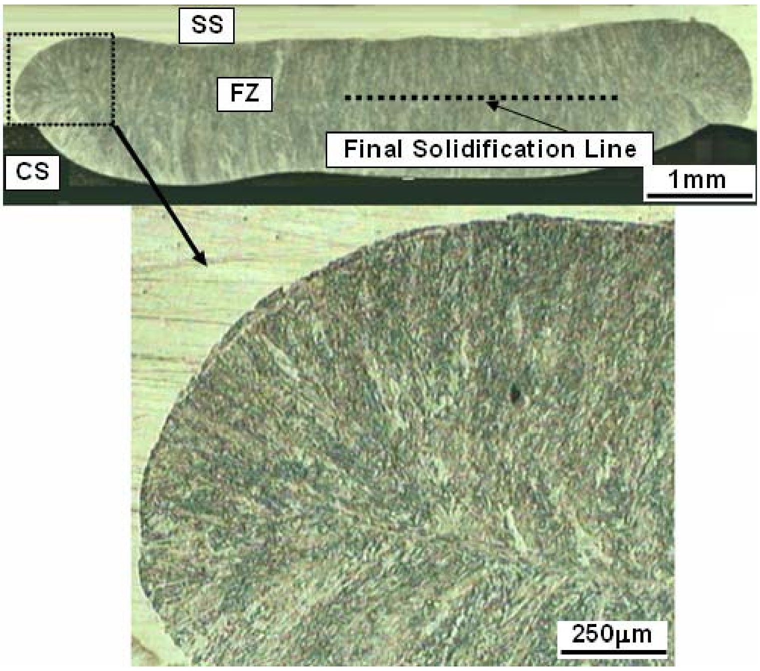


Fig.4 Structure of Dissimilar SS/CS spot weld

Two interesting features of the FZ are as follows:

(i) Asymmetrical shape of the weld nugget. The FZ size and the penetration depth of the SS side are larger than those of the CS side. Differences in the thermal conductivity and electrical resistivity of two steel sheets lead to an asymmetrical weld nugget in dissimilar metal joints. Thermal conductivity and electrical resistivity significantly affect weld nugget formation and weld nugget growth. It is reported that the electrical resistivity of austenitic stainless steel and low carbon steels are, 72 and 12μΩcm [11], respectively. Lower electrical resistance of carbon steels, which is even lower for low carbon galvanized steel sheet, and its higher thermal conductivity compared to stainless steel leads to smaller FZ size in the former.

(ii) Unlike similar RSW joints, final solidification line is not located at sheet/sheet interface but shifts to the higher resistively side; here, stainless steel. Since the FZ size at sheet/sheet interface is the main controlling factor of the spot weld mechanical performance; shifting the final solidification line form sheet/sheet interface towards higher resistively side can affect the mechanical performance.

Fig.5 shows the hardness profile of the CS/SS RSW. As can be seen, the hardness of the FZ is significantly higher than the hardness of both BMs. Weld FZ microstructure of dissimilar CS/SS RSWs can be predicted by constitution diagrams e.g., Schaeffler diagram [16]. It should be noted that the application of this diagram might be inaccurate due to the very high cooling rates of RSW process. The FZ microstructure of dissimilar CS/SS RSWs depends on the chemical composition of the BMs and the dilution (defined as the carbon steel to the weld nugget volume ratio). Dilution is controlled by welding parameters. In the applied welding conditions the dilution was measured as 40%. According to Schaeffler diagram, a martensitic structure is expected to from in the FZ, as confirmed by the much higher hardness of the FZ relative to the BMs.

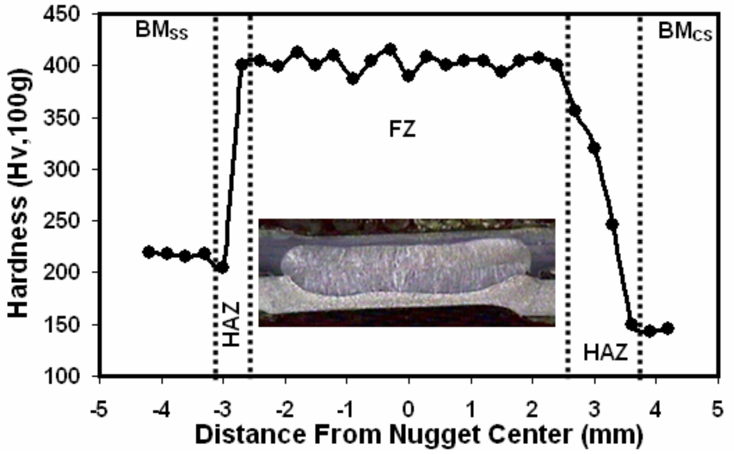


Fig.5 A typical hardness profile of SS/CS RSW

The HAZ of CS side experienced significant microstructure alterations as indicated by by hardness profile. However, it should be noted that, since austenitic stainless steel base metal is not transformable, no phase transformation occurs in the HAZ. However, grain structure of this region is affected by welding process. Some grain growth was observed adjacent to the weld nugget. It worth mentioning that the extent of grain growth for austenitic stainless steels is a lot less than ferritic steels [17].

A serious matter during austenitic stainless steel welding is the precipitation of chromium carbides in grain boundaries which can dramatically reduce corrosion resistance of the joint [17]. In this study, Murakami etching solution (10g KOH, 10g $K_3[Fe(CN)_6]$, 100 ml H_2O), which is very sensitive to chromium rich particles, was used to investigate the formation of chromium carbides in HAZ. However, no such particles were observed in this region which can be ascribed to resistance spot welding high cooling rate which in turn significantly reduces the holding time in the temperature range of chromium carbide precipitation. Low carbon content of the investigated steel hinders the formation of these detrimental precipitates, too.

Effect of welding parameters on weld attributes

Welding parameters can significantly affect the weld nugget growth and FZ microstructure. FZ sizes were measured at the sheet/sheet interface in the longitudinal direction on the metallographic cross section of the welds. Since the weld nugget shape is asymmetrical, the FZ size were measured at both side: weld nugget width at the sheet/sheet interface in carbon steel side (CS FZ size) and weld nugget width at the sheet/sheet interface in stainless steel side (SS FZ size). Fig.6 shows variation of FZ sizes as a function of welding current. Fig.7 shows macrograph of dissimilar SS/CS RSWs at various welding current. As can be seen, the FZS of both stainless and galvanized steel sides increases with the welding current at a decreasing rate with the exception of really high currents (more than 11.5 kA) which show a slight decrease in the FZS due to expulsion.

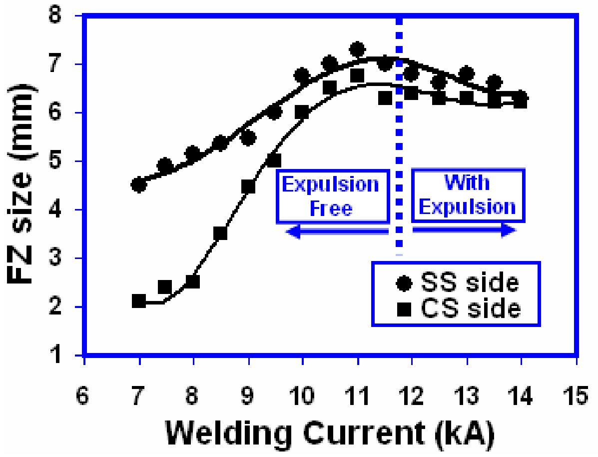


Fig.6 Effect of welding current on the FZ size in both SS and CS side

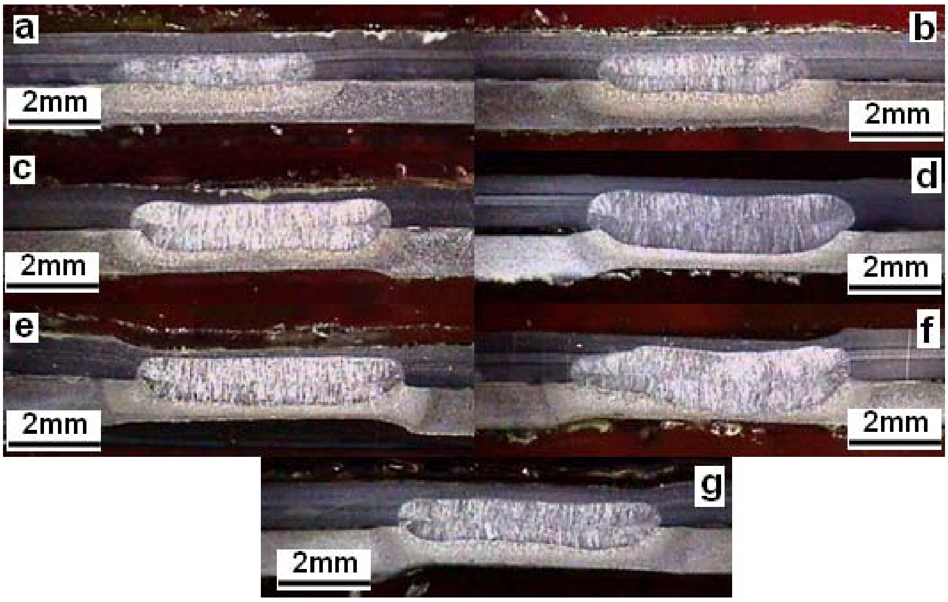


Fig.7 Effect of welding current on the weld nugget growth:
(a) 8kA, (b) 9kA, (c)10 kA,(d)11kA,(e)12kA,(f)13kA,(g)14 kA

Fig.8 shows variation of FZ hardness as a function of welding current. FZ Hardness of CS/SS RSWs is a function of its microstructure which in turns governs by the FZ chemical composition which is a mixture of composition of SS and CS.

According to the Schaeffler diagram the FZ microstructure dictated by dilution ratio. As can be seen, increasing welding current up to 8.5 kA increases dilution ratio. However, after this point, dilution ratio is almost independent from welding current. As can be concluded from Schaeffler diagram increasing dilution ratio of SS304 and CS beyond 21% leads to formation a martensitic structure. According Schaeffler diagram and corresponding dilution ratios, spot welds made at welding current lower than 8.5kA exhibit Ferrite+Austinite+Martensite microstructure as verified by low FZ hardness value of these welds.

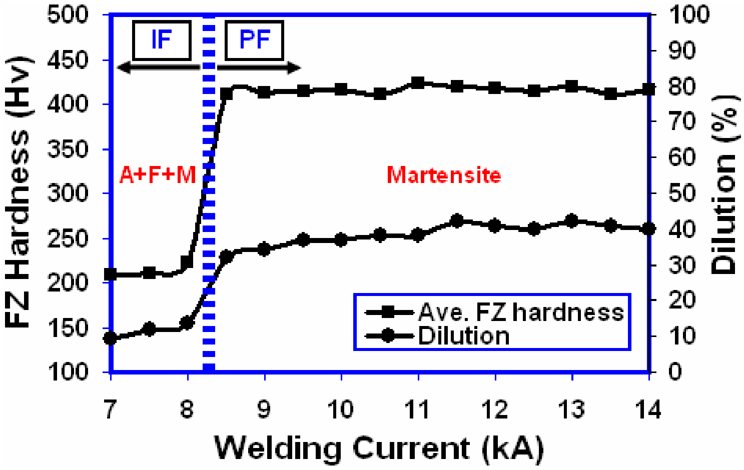


Fig.8 Effect of welding current on the FZ hardness, dilution, failure mode and the predicted microstructure using Schaeffler diagram

Criteria for selection of optimum welding parameters

In order to selection of optimum welding parameters for SS/CS dissimilar resistance spot welding the following points should be considered:

i) FZ size is the most important parameters in determination of mechanical properties of RSWs.The larger the FZ size, the higher the strength is. FZ size is governed by heat generated during welding process which is in turn controlled by welding parameters. Generally, the higher the heat input (i.e. higher welding current, higher welding time and lower electrode force), the higher FZ size is.

ii) Electrode indentation depth should be kept at a minimum value. It has been shown that increasing indentation depth; decreases the weld load carrying capacity and the energy absorption capability [6, 18]. The electrode indentation depth depends on electrode pressure and the temperature of electrode/sheet interface. The later is a function of heat generated during welding. Increasing heat input increases the electrode indentation depth.

iii) Severe expulsion (i.e. molten metal ejection from weld nugget) should be prevented during welding. Increasing heat input increases the temperature of electrode/sheet interface which in turn increases the degree of plastic deformation that can occur in the sheet surface under electrode pressure. Spot welds with expulsion exhibit severe electrode indentation. Also, expulsion can reduce weld nugget size [6].

iv)Welding parameters should be adjusted such that the pullout failure mode is obtained during mechanical testing. Spot welds during their service life experience complex loading condition including shear, tensile, compression, bending and torsion stresses. In this work, however, the tensile-shear laboratory test can be considered as the baseline for failure mode based on the fact that the RSWs show greater tendency to fail in interfacial failure mode during this loading condition in comparison to other ones such as peel test, coach peel test and cross tension [9]. Accordingly, failure mode during tensile-shear test is a conservative measure for quality control of spot welds. RSWs failed in pullout mode during tensile-shear test are expected to fail in pullout mode during cross-tension, peel and chisel tests. Pouranvari et al. [7] proposed a simple analytical model to predict minimum FZS required to ensure pullout failure mode of spot welds during the tensile-shear test. Critical FZS (d_{Cr}) was attributed to sheet thickness (t) and weld nugget to failure location hardness ratio (H_{WN}/H_{FL}), as follows:

$$d_{Cr} = 8\,t\,\frac{H_{FL}}{H_{WN}} \tag{1}$$

According to this model, the ratio of the hardness of FZ to the hardness of pullout failure location is the most important metallurgical factors governing the failure mode of RSWs. For a constant sheet thickness, those spot welds having low H_{FZ}/H_{FL} exhibit higher susceptibility to the interfacial failure mode. High hardness of the fusion zone relative to the failure location encourages the failure initiation in the base metal or HAZ.

According to this model, it is needed to adjust welding parameters so that the dilution is sufficiently high to produce a martensite structure in the FZ. For a quantitative analysis of failure mode, the minimum FZ size to ensure pullout failure mode during the tensile-shear test can be calculated as follows:

Failure location during tensile-shear test is where the hardness is lower. Therefore, the failure location during tensile-shear test of SS/CS RSWs is at CS base metal. By substituting H_{WN}/H_{CS}=2.7 (the value is approximately constant for all spot welds made with I_W>8kA) and t_{GS}=1.1mm in the equation, critical weld size is calculated to be 3.26mm. Therefore, welding parameters should be adjusted such that spot weld with nugget size greater than 3.26 mm can be obtained. Effect of welding current on the failure mode of SS/CS RSWs is shown in Fig.7.

v) Welding parameters should be adjusted such that the carbide precipitation in the HAZ of stainless steel kept at the minimum value. The precipitation of Cr-carbide depends on the peak temperature which experienced by the HAZ and the holding time in the temperature range of chromium carbide precipitation [17]. Increasing the welding current and welding time increases the risk of carbide formation.

vi) To achieve a sound weld (i.e. without porosity and void), a sufficient electrode force and holding time should be used. Sufficient electrode force and holding time guarantees the complete solidification of liquid weld nugget under proper electrode pressure. It has been proved that longer holding times and higher electrode force help to reduce shrinkage voids. However, excessive electrode force may reduce the weld nugget size.

Fig.9 shows the effect of welding current on the peak load and energy absorption of SS/CS RSWs. As can be seen increasing welding current up to 11.5kA leads to increasing peak load and energy absorption. However, increasing welding current beyond 11.5 kA does not affect peak load. However, welding currents beyond 11.5kA reduce energy absorption of spot welds. According to above criteria, the following welding parameters were selected to obtain a spot weld with good quality:

Electrode force: 4.2 kN
Welding time: 12 cycles
Welding current: 11-12 kA

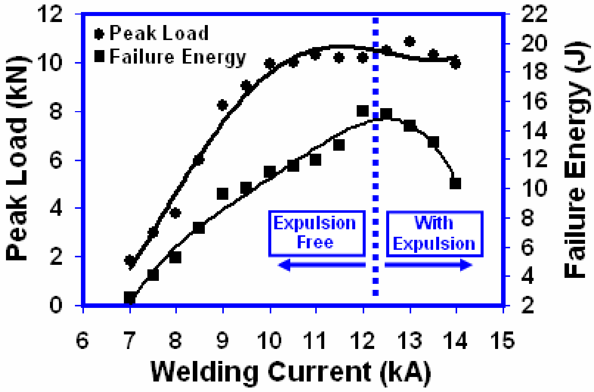


Fig.9 Effect of welding current on the peak load and failure energy of SS/CS dissimilar RSW

With the use of these welding parameters a spot weld with sufficient weld nugget size (about 6.2-6.5 mm), without expulsion, with a limited electrode indentation, without porosity and voids in the welds and without carbide-precipitation was obtained (See Fig.10). Also, this specimen was failed in pullout failure mode (see Fig.10).

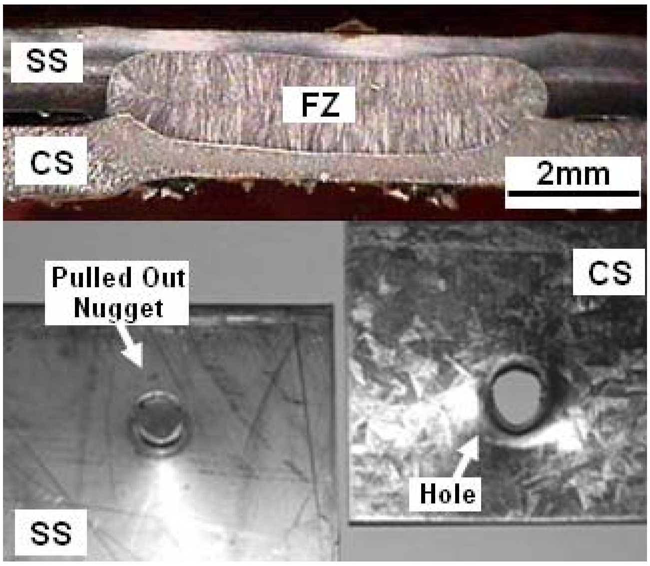
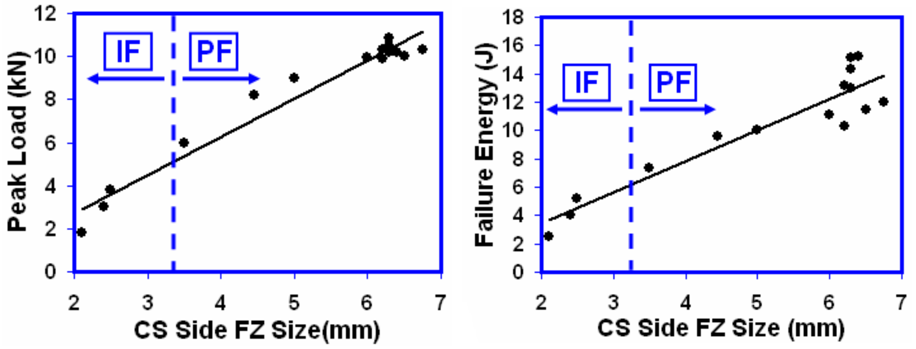


Fig.10 Macrostructure and fracture surface of dissimilar SS/CS RSW made at optimum welding conditions

The mechanical strength of spot welds is determined mainly by the weld nugget size at sheet/sheet interface. As mentioned above, the weld nugget of SS/CS RSW is asymmetrical and the FZ size of CS side is lower than SS side. Therefore, the mechanical strength of SS/CS RSWs is determined by CS side FZ size. Fig.11 shows the effect of CS side FZ size on the peak load and failure energy of SS/CS RSWs. As can be seen there is direct relations between mechanical performance (peak load and energy absorption) and FZ size of CS side.



a b

Fig.11 Effect of FZ size of CS side on the a) peak load and b) failure energy of SS/CS dissimilar RSW

Comparsion of mechanical properties of similar and dissimilar joints

Peak load of the RSWs depends on several factors including the physical weld attributes (mainly FZ size and indentation depth), the failure mode and the strength of the failure location.

Failure energy of RSWs, measured as the area under the load-displacement curve up to the peak point, can be expressed as follows:

$$\textit{Energy Absorption} = \int_{o}^{l_{\max}} F\,dl \propto P_{\max} \times l_{\max} \qquad (2)$$

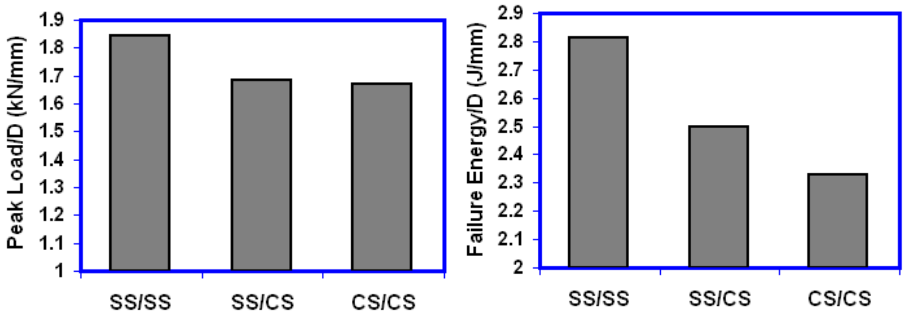
Where, P_{max} is the peak load and l_{max} is the maximum displacement, corresponding to the peak load. Maximum displacement (l_{max}) which represents ductility of the spot welds depends on the ductility of the failure location. Therefore, the energy absorption depends on the factors governing the peak load and the ductility of the failure location.

Three sheet combinations including SS/SS, CS/CS and SS/CS were spot welded as per welding parameters given in Table 2.

Table2. Welding schedules used to produce spot welds with set-up weld size of 5.5(t)$^{1/2}$

Joint type	Welding current	Welding time	Electrode force
CS/CS	11.5 kA	12 cycles	4.2 kN
SS/SS	10 kA	12 cycles	4.2 kN
CS/SS	11 kA	12 cycles	4.2 kN

The selected welding schedules were designed to produce a target weld size of 6mm or $5.5(t)^{1/2}$, where t is the sheet thickness, which is commonly used as maximum weld nugget size without expulsion. To account for the differences in FZ sizes, the values of peak load and failure energy were normalized by dividing to FZ size (D). As can be seen in Fig.12a, peak load of SS/SS is higher than CS/CS RSWs. This is function of its higher BM strength. However, peak load of CS/CS and SS/CS is nearly same. This is due to the fact that the PF failure mode of SS/CS welds is initiated from CS base metal, as indicated in Fig.10. As a direct result of this phenomenon, it can be concluded that the pullout peak load of the SS/CS is dictated by the CS base metal tensile strength. Despite the same peak load of SS/CS and CS/CS, the failure energy of former is higher (see Fig.12b). This can be related to higher ductility and strain hardening coefficient of SS which helps increasing plastic deformation during process of pullout failure. High failure energy of SS/SS weld is a function of SS base metal higher peak load and high ductility as well as its high strain hardening coefficient.



a b

Fig.12 Comparison of mechanical properties of similar and dissimilar combination a) Peak load b) failure energy

Conclusions

Resistance spot welding of dissimilar AISI 304 austenitic stainless steel and AISI 1008 low carbon steel is investigated. From this study the following conclusions can be drawn:

1-Compared to similar welds, weld nugget of dissimilar SS/CS RSWs has two distinct features: Asymmetrical shape (FZ size of SS side is greater than that of for CS side due to its higher resistivity) and shifting of final solidification line from sheet/sheet interface into the SS side. As a direct result, the mechanical performance of dissimilar SS/CS is determined by FZ size of CS side.

2-In dissimilar RSWs of low carbon and austenitic stainless steel, microstructure and hardness of the fusion zone which are controlled by dilution and fusion zone size of low carbon steel side mainly govern the failure mode. By increase in welding current, increasing fusion zone size coupled with the formation a martensitic fusion zone will lead to transition from interfacial to pullout failure mode.

3-It was shown that generally there is a direct relation between mechanical performance (peak load and failure energy) and FZ size of low carbon steel side.

4- The peak load of CS/CS and SS/LCS was nearly same due to the fact that the pullout failure mode of SS/CS welds is initiated from CS base metal. However, the failure energy of the later was greater than the former weld which is a function of higher ductility of SS that helps increasing plastic deformation during process of pullout failure.

Acknowledgment:

Authors would like to thank Islamic Azad University, Najafabad Branch for providing funding for this research project.

List of abbreviations:

BM: Base Metal
CS: Carbon Steel
FZ: Fusion Zone
FZS: Fusion Zone Size
HAZ: Heat Affected Zone
IF: Interfacial Failure Mode
l_{max} :Maximum displacement corresponding to the peak load.
P_{max} :Peak load
PF: Pullout Failure Mode
RSW: Resistance Spot Weld
SS: Stainless Steel

Refrences

[1] X. Sun, E. V. Stephens, M. A. Khaleel, Engineering Failure Analysis,15 (2008),356-367.
[2] J C Feng, Y R Wang , Z D Zhang, Sci. Technol. Weld. Joining, 11(2006), 154-162.
[3] H. Zhang, J. Senkara, Resistance welding: fundamentals and applications, Taylor & Francis CRC press; 2005.
[4] M. Zhou, H. Zhang and S. J. Hu: Weld. J., 82 (2003), 72s–77s.
[5] Zuniga S. M., Predicting overload pull-out failures in resistance spot welded, Ph.D. thesis, Stanford University,1994.
[6] Goodarzi M., Marashi S.P.H., Pouranvari M, J. Mat. Process. Tech, 209 (2009), 4379-4384
[7] Pouranvari M., Asgari H. R., Mosavizadeh S. M., Marashi P. H, Goodarzi M., ,Sci.Technol. Weld. Joining, 12(2007), 217-225.
[8] Chao Y. J., Failure mode of resistance spot welds: interfacial versus pullout, Sci. Technol. Weld. Joining, 8 (2003),133-137.
[9] Marya M.and Gayden X.Q., Weld J., 84 (2005),197s–204s.
[10] V. H. Baltazar Hernandez, M. L.Kuntz, M. I. Khan, Y. Zhou, Sci Tech Weld Join, 13 (2008), 769-776.
[11] M. Alenius, P. Pohjanne, M. Somervuori and H. Hanninen: Weld. J., 85 (2006), 305s–313s.

[12] R. Kacar and A. Hasanbasoglu: Mater. Design, 28 (2007), 1794–1800.
[13] A. Hasanbasoglu , R. Kacar. J. Mater. Sci. Tech, 22(2006),375–381.
[14] S. Poggio, M. Ponte, C. Gambaro, J. Adamowski, Resistance spot welding of advanced high strength steel DP600, Super High Strength Steels. Proc. 1st International Conference, Rome 2005, 1-13.
[15] Recommended Practices for Test Methods and Evaluation the Resistance Spot Welding Behavior of Automotive Sheet Steels, ANSI/AWS/SAE D8.9-97.
[16] A. L. Schaeffler, Metal Progress, 56(1949), 680-680B.
[17] C. Lippold , D. J. Kotecki, Welding Metallurgy and Weldability of Stainless Steels, John Wiley & Sons, 2005.
[18] Pouranvari M., Abedi A., Marashi P., Goodarzi M., Sci. Technol. Weld. Joining, 13 (2008), 39-43.