**Electrochemical Behavior of Dissimilar Carbon-Stainless Steel RSW Joints**

Results showed formation of martensite in the fusion zone produced elevated hardness values and was detrimental to corrosion resistance of the material in acid media

**ABSTRACT**

In the present investigation, the electrochemical behavior of dissimilar welds between austenitic stainless steel and low-carbon steel obtained by resistance spot welding was investigated. The results obtained showed the formation of martensite in the fusion zone produced elevated hardness values (~ 480 HV) and was detrimental to the corrosion resistance of the material in acid media (0.5M H₂SO₄ containing naturally dissolved O₂). The susceptibility of the welded joints to hydrogen embrittlement was studied by applying cathodic charging in acid solution, which led to a 42 ± 5% reduction in maximum elongation compared to noncharged specimens.

**KEYWORDS**

- Dissimilar Welding
- Resistance Spot Welding (RSW)
- Electrochemical Impedance Spectroscopy
- Potentiodynamic Polarization
- Hydrogen Embrittlement

**Introduction**

The resistance spot welding (RSW) process is widely used in industry today due to its elevated productivity, ease of automation, low cost, and absence of potentially hazardous fumes or gases, among other reasons. In a typical RSW joint, a localized union is produced between overlapped sheets by the passage of an electrical current, which causes heat generation by Joule effect. The electrodes employed also serve the purpose of applying force to the joint to assist the formation of a metallurgical bond between the materials. The RSW process is applied prominently in the automotive industry, and it is estimated that between 2000 and 5000 spot welds can be found in a modern vehicle (Ref. 1).

The union of dissimilar materials by welding can be a complex technical issue because of differences in chemical composition and microstructures, as well as mechanical or physical properties. For instance, differences in the thermal expansion coefficient may contribute to the formation of residual stresses in dissimilar joints between ferritic and austenitic steels (Ref. 2), and brittle intermetallic compounds may be found in dissimilar welds of aluminum and steel (Ref. 3). In this context, the RSW process is interesting because it provides a small-volume fusion zone in comparison to arc welding processes, which may contribute to minimizing material incompatibilities. In fact, it is worth noticing the number of studies performed in recent years with the objective of investigating the union of structural carbon steels and stainless steels by RSW (Refs. 4–8), providing a cost-effective alternative to the use of bulk corrosion-resistant materials and the means to integrate stainless steels with conventional structural steels in new designs.

Most investigations carried out to date concerning dissimilar RSW between carbon and stainless steels have focused on the mechanical behavior and microstructure formation of the welded joints (Refs. 4–6, 9–11) with relatively less attention directed toward the actual electrochemical behavior (Refs. 8, 12). In dissimilar RSW between carbon and stainless steels, the fusion zone (FZ) microstructure is reported to be predominantly martensitic, due to base metal dilution and elevated cooling rates (Ref. 5), in contrast with the FZ present in similar austenitic stainless steel RSW, reported to consist of dendritic austenite with δ-ferrite in interdendritic regions (Refs. 13–15). These modifications can be detrimental to the corrosion resistance of the joints because of the reduction in Cr and Ni levels in the FZ and may also impair mechanical integrity in hydrogen-containing media because the presence of martensite increases susceptibility to hydrogen embrittlement (Refs. 12, 16–18). As such, in the present experimental work, dissimilar RSW joints between austenitic stainless steel and low-carbon
steel in acid media were investigated, with the objective of exploring the relation between the microstructure in the FZ with the electrochemical properties of the weld.

**Experimental Procedure**

**Materials**

The materials used in the welding experiments were 100 × 25 × 1 mm sheets of austenitic stainless steel (nominally AISI 316L) and low-carbon steel (nominally AISI 1008), with the chemical composition presented in Table 1 (the Cr- and Ni-equivalent values of each steel are also presented). The registered composition matches the requirements for the carbon steel standard specification, but in the case of the austenitic stainless steel, the contents of Ni and Mo were found to be smaller than required. The joints were positioned such that a 25 × 25 mm² overlap was formed in each case, at the center of which the electrodes were positioned for RSW.

The welding operations were carried out using laboratory RSW equipment with a maximum power output of 15 kVA, fixed welding time of 1 s, and welding currents of 3.3, 6.4, 8.5, 11.2, and 13.8 kA. Similar (of both steels) and dissimilar welds were produced. The average surface roughness (Ra) of the stainless and carbon steel sheets were, respectively, 0.3 ± 0.1 µm and 1.3 ± 0.2 µm, and the materials were ground in 400-grit SiC paper before welding operations to remove surface contaminants. Truncated-cone Cu electrodes with a tip diameter of 8.3 mm and a tip angle of 27 deg were used for performing the welds. The electrodes were produced from C11000 electrolytic Cu alloy and were not seasoned before the experimental procedures. Prior to each welding experiment, the geometry of the electrode tip was verified and, when necessary, machined to ensure the same geometry for all test conditions.

**Mechanical Properties**

After joining, the mechanical strength of the welded specimens was evaluated by employing tensile-shear tests. A total of three tests were performed for each value of welding current. The results were obtained in the form of force (F) vs. displacement (Δl) curves, from which the peak load was obtained. The dissimilar joints that exhibited best performance (analyzed in terms of failure mode and peak load) were then selected for further analyses. The susceptibility to hydrogen embrittlement of the welded joints was also analyzed by tensile-shear tests by comparing results obtained before and after cathodic charging in a 0.5M H₂SO₄ solution containing 0.25 g/L NaAsO₂ at 100 mA/cm² for 24 h (Ref. 19). A hydrogen embrittlement index was determined based on the relative difference in maximum displacement between the charged and pristine samples (Ref. 20). All tensile-shear tests were performed using a 5-mm/min cross-head displacement speed.

Local hardness variations within the dissimilar weld were assessed by performing Vickers microhardness indentations along the cross section of selected joints. The tests were performed using a Shimadzu HMV tester with a 245.2-mN load (HV 0.025), 20-s load time, and 0.08-mm distance between indentations across a line that starts at the carbon steel base material toward the stainless steel base material through the FZ (see Fig. 2).

**Weld Nugget Characterization**

The cross-section morphology of the dissimilar weld produced with 13.8-kA welding current was analyzed by scan-
ning electron microscopy (SEM). The preparation procedure involved grinding and polishing down to a 1-μm finish in an Al₂O₃ suspension, and observations were made in a JEOL IT300 microscope equipped with an Oxford/X-Max³ energy dispersive x-ray spectroscopy (EDX) detector for semiquantitative chemical composition analysis.

Electrochemical Corrosion Behavior

The electrochemical corrosion behavior of the dissimilar welded joints was analyzed and compared with the stainless steel base material. The tests were performed by exposing the top surface of the spot weld (from the stainless steel side) to a 0.5M H₂SO₄ aqueous solution containing naturally dissolved O₂ at 25°C. Before corrosion testing, the surface of the spot welds was ground in 1000-grit SiC paper to produce a homogenous surface finish among the tested groups, then rinsed in water, followed by ethanol, and dried. A three-electrode setup was employed, with a Pt counterelectrode and Ag/AgCl in saturated KCl as reference electrode. A 400-mL volume horizontal cell prepared for flat specimens with a 5-mm-diameter orifice for exposing the samples to the electrolyte was used. The diameter of the electrochemical cell was chosen because it was smaller than the spot weld diameter (approximately 8 mm). Special care was taken during preparation of the corrosion tests to ensure the spot weld was centered relative to the orifice of the electrochemical cell, so the examined area consisted only of the welded region and did not incorporate the base material. Because of the relatively small analyzed surface, a total of five measurements were performed on different welded and reference samples.

During initial stabilization, the open circuit potential (OCP) was monitored for 1.5 h before analysis by electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization (PP). The EIS analysis was carried out at the stabilized OCP by applying a 10-mV sinusoidal excitation signal with frequencies varying from 100,000 to 0.01 Hz, whereas the PP scans were performed at a 0.2-mV/s rate in 1-mV steps from –0.5 to 1.5 V. The corrosion current density (i_corr) was determined by extrapolation of the cathodic Tafel line to the corrosion potential (E_corr) because of different metal dissolution reactions, which yield nonlinear or poorly defined anodic Tafel lines (Ref. 21).

Results and Discussion

Mechanical Properties

The results of the tensile-shear tests are presented in Fig. 1, in which peak load (F_max) is plotted as a function of welding current for similar carbon steel, similar stainless steel, and dissimilar carbon-stainless steel welds. The maximum peak load value obtained for the dissimilar welds was 6.3 ±
0.2 kN (standard deviation calculated from three measurements), as indicated. The lowest welding current setting (3.3 kA) was found to be insufficient for effectively producing the similar and dissimilar welds, and these joints were consequently not submitted to tensile-shear testing. For all situations, the peak load was found to increase with welding current, probably in connection with the increase in weld nugget size (Refs. 4, 22). Two failure mechanisms were identified, which were interfacial fracture and nugget pullout, in agreement with previous investigations (Refs. 23–25). In some cases, after nugget pullout, the sheet was torn along the heat-affected zone (HAZ) of the AISI 1008 steel. The interfacial fracture mode was not observed in the similar stainless steel joints, but was noticed on the remaining conditions for welding currents of 6.4 kA or less. For higher welding current values, all joints failed by nugget pullout. The change in failure mode from interfacial to pullout is expected with the increase in peak load. For small weld nuggets, shear stresses reach a critical value before tensile stresses cause necking and above a certain weld nugget size pullout failure is expected (Ref. 5).

Analysis of Weld Nugget

The dissimilar welded joints that exhibited highest peak load in the tensile-shear tests were selected for further examination (13.8-kA welding current). A cross-sectional overview of the weld nugget is presented in Fig. 2A, which highlights EDS chemical composition analyses at the center of the FZ and stainless steel base material and the line DD'.

Table 2 — Uniform Corrosion Parameters from Potentiodynamic Polarization Scans of Dissimilar RSW Joints (FZ) and Austenitic Stainless Steel Base Material (BM) in 0.5M H₂SO₄ Containing Naturally Dissolved O₂ at 25°C

<table>
<thead>
<tr>
<th></th>
<th>Ecorr (V/Ag-AgCl)</th>
<th>icorr (μA/cm²)</th>
<th>bc (V/dec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>–0.202 ± 0.01</td>
<td>10 ± 10</td>
<td>–0.115 ± 0.01</td>
</tr>
<tr>
<td>FZ</td>
<td>–0.224 ± 0.02</td>
<td>30 ± 20</td>
<td>–0.128 ± 0.02</td>
</tr>
</tbody>
</table>

Ecorr — Corrosion potential; icorr — corrosion current density; bc — cathodic Tafel slope

Table 3 — Passivity Characteristics Obtained from Potentiodynamic Polarization Scans of Dissimilar RSW Joints (FZ) and Austenitic Stainless Steel Base Material (BM) in 0.5M H₂SO₄ Containing Naturally Dissolved O₂ at 25°C

<table>
<thead>
<tr>
<th></th>
<th>Epp (V)</th>
<th>icrt (mA/cm²)</th>
<th>Ecp (V)</th>
<th>ipass (mA/cm²)</th>
<th>Etp (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>–0.150 ± 0.02</td>
<td>0.019 ± 0.01</td>
<td>–0.01 ± 0.05</td>
<td>0.002 ± 0.001</td>
<td>1.00 ± 0.00</td>
</tr>
<tr>
<td>FZ</td>
<td>–0.130 ± 0.04</td>
<td>0.033 ± 0.02</td>
<td>0.219 ± 0.06</td>
<td>0.004 ± 0.001</td>
<td>1.04 ± 0.01</td>
</tr>
</tbody>
</table>

Epp — potential for primary passivation; icrt — critical current density for passivation; Ecp — potential for complete passivation; ipass — passive current density; Etp — transpassive potential
Table 4 — EIS Parameters Obtained for the Dissimilar RSW Joints (FZ) and Austenitic Stainless Steel Base Material (BM) in 0.5M H₂SO₄ Containing Naturally Dissolved O₂ at OCP

<table>
<thead>
<tr>
<th></th>
<th>Rₛ (Ωcm²)</th>
<th>Rₛ (Ωcm²)</th>
<th>Rₛ (Ωcm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>4.16</td>
<td>264.0</td>
<td>1220</td>
</tr>
<tr>
<td>FZ</td>
<td>795</td>
<td>41.6</td>
<td>66.0</td>
</tr>
</tbody>
</table>

Rₛ — solution impedance; Rₛ — polarization resistance of the metal/electrolyte interface; Rₛ — polarization resistance of the oxide/electrolyte interface
Hydrogen Embrittlement

The susceptibility to hydrogen embrittlement of the dissimilar welded joints was analyzed by applying tensile-shear tests before and after cathodic charging at 100 mA/cm², and the results are presented in Fig. 6. It is possible to notice that after hydrogen permeation, both peak load (Fₘₐₓ) and maximum elongation (Δlₖₐₓ) were reduced. The relative loss in Δlₖₐₓ (from 6.60 ± 0.8 mm to 4.90 ± 0.05) was used to compute the hydrogen embrittlement index, and the value obtained was 42 ± 5% (standard deviation of three tested samples), which indicates the welded region is sensitive to the presence of hydrogen, a consequence of its predominantly martensitic microstructure. With regard to the failure mechanism, it is worth observing that prior to hydrogen permeation, the dissimilar welded joint failed by nugget pullout followed by tearing of the AISI 1008 carbon steel sheet. After hydrogen charging, failure still occurred by pull-out, but a complete withdrawal of the weld nugget was observed from the stainless steel side of the joint instead (the side exposed to hydrogen charging), as shown in Fig. 7.

It is important to notice that both the sensitivity to hydrogen and the reduction in corrosion resistance noticed in the previous section are related to the exposure of the martensitic FZ microstructure to the acid environments in which these results were obtained. This, in turn, is a consequence of the complete penetration of the welded joints. Thus, the results presented here indicate that if the electrochemical behavior of the base material is to be preserved, the nugget size of the dissimilar weld should be controlled to avoid formation of the typical FZ microstructure on the surface of the welded joints.

Conclusions

In the present work, dissimilar joints of low-carbon steel and austenitic stainless steel were produced by RSW and evaluated in terms of mechanical properties, microstructure, and electrochemical behavior. The dissimilar welds exhibited a positive relation between welding current and peak load in tensile-shear tests below the maximum welding current of 13.8 kA, and elevated hardness in the FZ (~ 480 HV). The presence of martensite in the FZ of the welded joints, along with the reduction in the amounts of alloying elements such as Cr and Ni, were connected with a reduction in corrosion resistance, both in terms of uniform corrosion and passivity behavior. Finally, the FZ of the dissimilar welded joints were found to be susceptible to hydrogen embrittlement, leading to a significant loss ductility.

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References

143-s to 147-s.


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