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Effects of resistance spot welding parameters on microstructures and mechanical properties of dissimilar material joints of galvanised high strength steel and aluminium alloy

W. H. Zhang, X. M. Qiu, D. Q. Sun* and L. J. Han

Intermediate frequency resistance spot welding has been adopted to join dissimilar materials of H220YD galvanised high strength steel and 6008 aluminium alloy. The effects of welding current and welding time on microstructures and mechanical properties of the welded joints were investigated. A thin intermetallic compound layer composed of Fe2Al5 phase and Fe4Al13 phase formed at the steel/aluminium interface. The interfacial intermetallic compound layer has higher nanohardness compared with the aluminium alloy nugget and galvanised steel. With increasing welding current (4–11 kA) and welding time (50–300 ms), the nugget diameter increased, the interfacial layer structure became coarser and the tensile shear load of the welded joints had an increased tendency. The maximum tensile shear load reached 3309 N at 9 kA for 250 ms. Crack initiated at the interfacial intermetallic compound layer of the tensile shear specimens, then propagated through the interfacial layer principally, and meantime through the aluminium alloy fusion zone near the interface partially.

Keywords: Resistance spot welding parameters, Dissimilar materials joints, Galvanised high strength steel, Aluminium alloy, Microstructures, Mechanical properties

Introduction

As problems of energy scarcity and environmental pollution become increasingly severe, the automotive industry has been devoted to reducing the vehicle weight and developing essentially fuel efficient vehicles of greater security performance. In order to realise automobile lightweight, both aluminium alloys, chosen as a substitution for steels in some certain portions of the body structure, and high strength steels have been extensively used.1,2 Consequently, a unique design of high strength steels and aluminium alloys with a hybrid structure to guarantee performance and cost, which can utilise functionalities of the dissimilar materials to the fullest extent, is investigated in automotive industry nowadays.3 An indispensable process in regard to promoting the widespread use of dissimilar material combination and multistructure methodology in automobile is the joining between high strength steels and aluminium alloys. As is known, there exist great inherent discrepancies in physical, thermal, electrical and mechanical properties between steels and aluminium alloys. Accordingly, it is difficult to obtain a reliable joint of steel to aluminium alloy by traditional fusion welding, as fusion welded joints exhibit multiple brittle intermetallic compounds, which readily result in degradation of joint mechanical behaviour.4,5 The auto makers still adopt mechanical joining techniques such as screwing, clinching and riveting to fabricate the hybrid structure of high strength steels and aluminium alloys to date. Self-piercing riveting (SPR) also offers a great potential and attract mass interest as an effective and energy efficient means, which has been increasingly used to join steels and aluminium alloys in automotive manufacturing.6,7 Nevertheless, SPR has certain inherent limitations in terms of joint appearance, the access restriction to certain joint positions, additional consumable items and joint corrosion resistance behaviour, while a key problem with respect to SPR lie in that high strength steels having poor ductility tend to rupture during riveting.8,9 In addition, solid state welding methods have been studied in the last few years to acquire a sound metallurgical joint, such as explosion welding,10 magnetic pulse welding,11,12 friction welding13,14 and friction stir welding.15–18 Although the joints obtained by the above means show reasonable performance to a certain extent, joint shape and size are restrained by equipment configuration and capacity. Tungsten inert gas welding–brazing19–21 and laser brazing22–25 are also carried out to join dissimilar materials of steels and aluminium alloys; the results indicate that intermetallic compound layers...
that formed at the interface are weak zones where cracks incline to initiate under the applied stress during mechanical behaviour testing.

Owing to the advantages of high adaptability, efficiency and ease of automation in high volume production, resistance spot welding (RSW) is one of the most commonly used welding methods in manufacture of vehicle body structures and components. However, few studies concerning RSW of steels and aluminium alloys are reported so far.26 Aiming to restrain the generation of reaction layers, transition materials of cold rolled aluminium clad steel strips are introduced to facilitate RSW of mild steels to aluminium alloys.27,28 However, welded joints with transition materials have lower fatigue strength as compared with SPR joints. Besides, potential cost increase will be a problem to be solved as a result of the high difficulty of aluminium clad steel strip fabrication. Another means known as RSW with cover plates has been investigated to achieve steel/aluminium alloy joints nowadays.29,30 The cover plate is a common cold rolled steel sheet and is placed between the electrode and the aluminium alloy sheet during RSW. The investigation reveals that joints of dissimilar materials obtained by RSW with cover plates present an interfacial failure mode under cross-tension load, with interfacial strength of 6-509 MPa.30 Besides, the RSW with both transition materials and cover plates stated above add weight to the entire vehicle, going against requirements of weight reduction to some extent.28

To obtain a further understanding of dissimilar material resistance spot weldability of steels and aluminium alloys, the present work investigates the microstructure characteristic and mechanical behaviour of dissimilar material resistance spot welded joints of galvanised high strength steels and aluminium alloys, and effects of welding parameters.

Experimental

The materials used in this investigation were H220YD-Z100 galvanised high strength steel sheets with 1-0 mm thickness and EN AW 6008-T66 aluminium alloy sheets with 1-5 mm thickness. Their chemical compositions are given in Table 1. The H220YD steel sheets were provided with a 7 mm zinc coated layer for both surfaces by hot dip galvanisation. All sheet specimens were machined into the size of 100 × 25 mm. Before welding, the EN AW 6008-T66 aluminium alloy sheets were prepared by grade 1200 SiC abrasive paper polishing and degreasing with acetone; meanwhile, the H220YD galvanised steel sheets were merely degreased, and then ground, polished and etched with both Keller’s reagent in sequence to reveal the microstructure of the joints. The welding experiment was carried out using an intermediate frequency (IF) RSW machine equipped with an LHN4 type welding gun with a nominal power of 75 kVA, which provided higher energy efficiency and a more stable welding current compared with traditional industrial frequency RSW machine. In general, the traditional industrial frequency RSW machine outputs alternating current with a frequency of 50 or 60 Hz as a welding current, and it has some disadvantages such as inherent poor power factor (usually 0-4-0-5), great impulse peak impact on power supply network and low energy efficiency as a result of the existence of zero current during welding. Nevertheless, the IF RSW machine first supplies 1000 Hz frequency single phase alternating current to the secondary circuit by an inverter, and then outputs direct current as a welding current by means of a single phase full wave rectifier. The power factor of the IF welding system is nearly 1-0, the welding current is extremely stable due to less impact on power supply network and the control accuracy of welding current is higher than that of industrial frequency RSW technology. Besides, the energy efficiency is higher, as no zero current appears during welding process. Therefore, the IF RSW technology is superior, especially for dissimilar material welding. An F type cap electrode (DIN ISO 5821-F16 × 20) was chosen with the hemispherical tip diameter of 16 mm, and the electrode cap was made utilising CuCr1Zr alloy (DIN ISO 5182 A2/2). Welding parameters were selected based on a previous preliminary test. In this study, IF resistance spot welding were carried out with welding current ranging from 4 to 11 kA and welding time between 50 and 300 ms at a constant electrode force (2 kN) and maintaining time (200 ms).

After welding, metallographic specimens for microstructure examinations were obtained by cross-sectioning the welded joints through the weld nugget centre of the dissimilar materials perpendicular to specimens’ surface plane. Then, the specimens’ cross-sections were ground, polished and etched with both Keller’s reagent for 3-5 s and 4% HNO3 in ethanol solution for 5-9 s in sequence to reveal the microstructure of the joints. Microstructures and compositions were examined using an LXT OLS 3000 type confocal scanning laser microscope and a scanning electron microscope (SEM, Hitachi S-3400N) with energy dispersive spectroscopy (EDS) and EDAX. A D8 Discover with GADDS micro-X-ray diffractometer with Cu Kα radiation was used.

Table 1 Chemical compositions of H220YD high strength steel and EN AW 6008-T66 aluminium alloy

<table>
<thead>
<tr>
<th>Elements, wt-%</th>
<th>C</th>
<th>Si</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Zn</th>
<th>Ti</th>
<th>V</th>
<th>S</th>
<th>P</th>
<th>Nb</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>H220YD</td>
<td>0-007</td>
<td>0-09</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0-51</td>
<td>...</td>
<td>...</td>
<td>0-01</td>
<td>...</td>
<td>0-007</td>
<td>0-05</td>
<td>0-02</td>
</tr>
<tr>
<td>EN AW 6008-T66</td>
<td>...</td>
<td>0-56</td>
<td>0-15</td>
<td>0-19</td>
<td>0-45</td>
<td>0-07</td>
<td>0-007</td>
<td>0-02</td>
<td>0-08</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>Balance</td>
</tr>
</tbody>
</table>
to analyse phase compositions of the interface in the weld nugget and fracture surfaces of the joints. A Hysitron TI 900 TriboIndenter nanomechanical test instrument was employed to measure the nanohardness distribution of the interface in the weld nugget, and the tensile shear tests of the welded joints were carried out using an MTS 810-22M material test system with 100 kN axial force capacity at a crosshead speed of

a H220YD side, 5 kA, 250 ms; b EN AW 6008-T66 side, 5 kA, 250 ms; c H220YD side, 9 kA, 300 ms; d EN AW 6008-T66 side, 9 kA, 300 ms

2 Appearances of welded joints at different welding currents and welding times

3 Cross-sections of welded joints at different welding currents and welding times

a 5 kA, 250 ms; b 7 kA, 250 ms; c 9 kA, 250 ms; d 8 kA, 100 ms; e 8 kA, 200 ms; f 8 kA, 300 ms
Especially, the tensile shear load was evaluated by the average value of three specimens under the same welding condition.

**Results and discussion**

**Joint appearances**

Figure 2 shows the appearances of dissimilar material IF resistance spot welded joints of H220YD galvanised steel to EN AW 6008-T66 aluminium alloy at various welding parameters. The joint on the steel side exhibited an expulsion free appearance with a shallow indentation depth, while an ellipsoid shaped spot indentation appeared on the aluminium alloy side where softening of the aluminium alloy material was observed at the welding current of 5 kA and welding time of 250 ms, as shown in Fig. 2a and b. With increasing the welding current and welding time, the welded joint appearances became irregular with severe expulsion occurrence on galvanised steel side and material melting on the aluminium alloy side, as illustrated in Fig. 2c and d. In this investigation, it was found that the alloying between the electrode and workpiece was so severe that the electrode could hardly be separated from the galvanised steel surface when welding current exceeded 9 kA at welding time of 300 ms.

Figure 3 shows the cross-sections of the welded joints under different welding conditions. As can be seen, the welded joint was composed of a melted aluminium alloy nugget and a steel heat affected zone, and hence, it could be regarded as a special brazed joint to some extent, where the melted aluminium alloy spread on solid steel surface during welding. With increasing the welding current and time, the aluminium alloy molten zone expanded, and the indentation depth increased simultaneously. An intruding of the molten aluminium alloy into the galvanised steel appeared at the centre of the weld interface (aluminium alloy bugling), when the aluminium alloy surface contacting the electrode started to melt, owing to the added press by the electrode.

Figure 4 exhibits the effects of welding parameters on weld nugget diameters. The weld nugget diameter increased with increasing welding current at welding times of 150 and 250 ms (Fig. 4a). The weld nugget with 2.7 mm diameter formed at a welding current of 5 kA for welding time of 150 ms, and it increased to 5.6 mm at a welding current of 11 kA. In the meantime, the weld nugget diameter ranged from 2.4 mm at 4 kA welding...
current to 5.7 mm at 9 kA welding current under constant welding time of 250 ms. Similarly, the weld nugget diameter had an increased tendency with the increase in welding time (Fig. 4b). The nugget diameters varied from 0 and 3.6 mm to 5.0 and 5.3 mm with increasing welding time from 50 to 150 ms for welding currents of 8 and 9 kA respectively. After 150 ms, the nugget diameters for both constant currents presented gradual changes, attributing to equilibrium between welding heat input and heat extraction. It should be noted that the welding parameters also influenced weld indentation greatly in the range of welding currents and welding times tested. The thickness reduction in percentage of the initial thickness of joints before welding was chosen to represent indentation degree. As illustrated in Fig. 5, the joint thickness reduction percentage increased gradually when welding current and welding time increased, and the maximum value of 33.4% was obtained at 9 kA for 300 ms. The behaviours concerning the varying tendencies of weld nugget diameter and indentation depth under different welding parameters were considerably dependent on the change of welding heat input. As heat input increased by means of increasing welding current and welding time, more
molten aluminium alloy and galvanised steel with a higher temperature were acquired, which resulted in the increases in nugget diameter and indentation size.

**Joint microstructures**

Figure 6 shows SEM and optical microstructures of the joint obtained at 9 kA for 300 ms, and analysis positions are plotted from A to G (Fig. 6a). From Fig. 6b, an irregular coarsened ferrite structure was observed at the steel heat affected zone. A cellular dendritic crystal structure developed at the boundary of the aluminium alloy nugget, epitaxially from the aluminium alloy base metal, which oriented in the direction of heat flow (Fig. 6c). Meanwhile, equiaxed grains were generated at the bottom of the aluminium alloy sheet contacting the electrode (Fig. 6d), owing to a higher thermal supercooling degree being obtained during the initial stage of solidifying as a result of the better thermal conductivity of CuCr1Zr alloy electrode (320 W m\(^{-1}\) K\(^{-1}\)) compared to the EN AW 6008-T66 aluminium alloy (150 W m\(^{-1}\) K\(^{-1}\)). The temperature gradient of liquid area in front of the liquid/solid interface decreased as the aluminium alloy pool solidified, and simultaneously, the segregation of elements, such as Mg and Si, gradually increased. As a result, large constitutional supercooling was achieved, and a finer dendritic structure developed (Fig. 6e and d). However, the aluminium alloy nugget near the steel/aluminium alloy interface exhibited a coarser grain structure (Fig. 6e), which was mainly attributed to the lower thermal conductivity of galvanised steels. Reaction layers with intermetallic compounds were formed at the steel/aluminium alloy interface, and the microstructure features of the reaction layers in terms of morphology and thickness varied with position at the interface (Fig. 6f–h). A decreasing tendency for the thickness of the interfacial intermetallic compound layer from the weld centre to periphery was observed. At the weld centre, the intermetallic compound layer presented a two layered structure in thickness direction plotted as I and II, as shown in Fig. 6f: a compact lath structure with \(~5\)–0 \(\mu\)m thickness beside the galvanised steel was formed (layer I), while long needle-like phases appeared with front orienting towards the aluminium alloy nugget, whose thickness was unequal (about 2–5–8 \(\mu\)m), as certain needles interspersed in the nugget (layer II). The interfacial intermetallic compound layer with thickness of \(~2\)–0 \(\mu\)m at the intermediate region between the weld centre and periphery exhibited a partially tongue-like morphology in the galvanised steel side and an extremely fine needle-like structure in the aluminium alloy side (Fig. 6g). Figure 6h presents a thinner interfacial layer of merely 0.8 \(\mu\)m at the peripheral region of the weld.

Table 2 shows the EDS analysis results of interfacial intermetallic compound layer in the weld, and the analysed locations are plotted as A, B and C in Fig. 6f and D in Fig. 6g. According to the Fe–Al phase diagram, the layer compositions were in accordance with Fe\(_2\)Al\(_5\) and Fe\(_4\)A\(_13\), substantially. So as to identify the phase compositions of the interfacial intermetallic compound layer, micro-X-ray diffraction analysis was carried out in a 100 \(\mu\)m diameter area localised at the interface in the weld centre, with analysis position plotted as E in Fig. 6a, and the result is shown in Fig. 7. The micro-X-ray diffraction profile exhibited that two phases of Fe\(_2\)Al\(_5\) and Fe\(_4\)A\(_13\) existed in the interfacial intermetallic compound layer, which agreed with the results determined by the EDS analysis well.

With increasing welding time from 100 to 300 ms at the welding current of 9 kA, the interfacial intermetallic compound layer at the weld centre became thicker (from 2–0 to 7–5–13 \(\mu\)m approximately), and the layer ranged from tongue-like to lath-like morphology beside the galvanised steel and from an extremely fine needle-like to a long needle-like structure in the aluminium alloy side, as shown in Figs. 6f, 6a and 6b. A similar changing

**Table 2** Energy dispersive spectroscopy analysis results of interfacial layer with positions taken from spots A–C in Fig. 6b and spot D in Fig. 6c.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Al wt-% at-%</th>
<th>Fe wt-% at-%</th>
<th>Zn wt-% at-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>54.15</td>
<td>71.07</td>
<td>44.21</td>
</tr>
<tr>
<td>B</td>
<td>62.76</td>
<td>78.56</td>
<td>34.88</td>
</tr>
<tr>
<td>C</td>
<td>66.23</td>
<td>80.27</td>
<td>33.21</td>
</tr>
<tr>
<td>D</td>
<td>52.46</td>
<td>69.62</td>
<td>46.41</td>
</tr>
</tbody>
</table>

7 Micro-X-ray diffraction profile of galvanised steel/aluminium alloy interface taken from position E in Fig. 6a.
trend concerning thickness and morphology for the interfacial intermetallic compound layer at the weld centre was obtained when the welding current increased from 5 to 9 kA at welding time of 250 ms, as shown in Fig. 8c–e. The changes were attributed to the different temperatures and times, which the interfacial layer experienced during welding. A higher temperature and/or interaction time will facilitate aluminium atoms to diffuse anisotropically into steel matrix and provided more energy for the reaction between Al and Fe atoms at the interface. Consequently, Al atoms had sufficient activation energy to escape the barrier of solidified reaction layer and react with Fe atoms, resulting in a thicker intermetallic compound layer with more flat aspect in the galvanised steel side.

Joint properties

To evaluate the mechanical properties of interfacial intermetallic compound layers, a nanoindentation test was performed, and the nanoindentation positions and nanohardness values are shown in Fig. 9. As can be seen, the aluminium alloy nugget presented the lowest nanohardness of ~1.1 GPa, and the nanohardness of the galvanised steel near the interface was higher (~2.1 GPa), while the maximum nanohardness was obtained in the interfacial reaction layer. The nanohardness of the lath shaped layer (Fe₃Al₄) beside the galvanised steel was averagely 8.7 GPa, compared with an average of 6.5 GPa for the needle-like layer (Fe₄Al₃) beside the aluminium alloy nugget.

Figure 10 shows the effects of welding current and time on tensile shear load of joints respectively. The results indicate that the joint tensile shear load increased in a quasi-linear characteristic with increasing welding current at welding times of 150 and 250 ms (Fig. 10a). At a relatively low welding current of 4 kA, the tensile shear load of 498 N was obtained at 250 ms, and a dramatic improvement in joint strength appeared when welding current increased from 4 to 9 kA, the maximum tensile shear load reaching 3309 N at 9 kA for 250 ms. The joint exhibited the tensile shear load of 3178 N at welding current of 11 kA for welding time of 150 ms. The changing tendency of tensile shear load was in good accordance with that of the weld nugget. Figure 10b shows an increasing tendency for joint tensile shear load with the increase in welding time at welding currents of 8 and 9 kA. Nevertheless, slow changing rate of joint tensile shear load with the increase in welding time (150–300 ms) and a slight reduction at 9 kA for 300 ms were observed, which was related to the fact that the weld nugget diameter presented a slow increasing tendency with increasing welding time (Fig. 4b). Moreover, the
interfacial intermetallic compound layer played an important role in inhibiting the mechanical behaviour as its thickness stayed at a high level.

In this study, the tensile shear specimens exhibited an interfacial failure mode. Figure 11 shows SEM images of the interfacial zone in weld of partially failed tensile shear specimen. The crack initiated at the brittle intermetallic compound layer (mainly in Fe$_2$Al$_5$ phase) under applied force (Fig. 11a). Then, the crack propagated through the intermetallic layer at the weld centre (Fig. 11b). Micro-X-ray diffraction analysis was adopted to detect fracture surface of the galvanised steel side, as shown in Fig. 12. As can be seen, it identified the existence of Fe$_2$Al$_5$ and Al on the fracture surface, which indicated that the crack eventually emanated at the brittle intermetallic compound layer and aluminium alloy nugget near the interface.

Conclusions

1. The dissimilar material IF resistance spot welded joints of galvanised high strength steels and aluminium alloys are composed of molten aluminium alloy nuggets and steel heat affected zones. Intermetallic compound layers form at the steel/aluminium interface. The interfacial layer consists of Fe$_2$Al$_5$ phase with lath-like or tongue-like morphology beside the steel and Fe$_4$Al$_{13}$ phase with needle-like morphology beside the aluminium alloy nugget, the morphology of which is considerably dependent on position in weld and welding parameters.

2. The increases in welding current (4–11 kA) and welding time (50–300 ms) result in the increase of nugget diameters with the maximum value of 5–8 mm achieved at 9 kA for 300 ms, simultaneously followed by a coarsening for the interfacial layer structure at the weld centre. The thickest interfacial layer comprised of lath-like with $\sim$5 mm thickness and long needle-like phase with unequal thickness (about 2–5–8 $\mu$m) is obtained.

3. The interfacial intermetallic compound layer has higher nanohardness compared with the aluminium alloy nugget and galvanised steel. Welding current and welding time have an obvious effect on the tensile shear load of the welded joints by changing nugget diameters and the interfacial layer structure. The maximum tensile shear load reaches 3309 N at 9 kA for 250 ms. Cracks initiate at the interfacial layer (chiefly in Fe$_2$Al$_5$ phase) of the tensile shear specimens and propagated mainly through the interfacial layer and partially through the aluminium alloy fusion zone near the interface.

References