1. Introduction

Reducing emission of harmful gases and energy consumption is the major challenge in automotive industry with the aggravation of environmental pollution, and automotive lightweight is recognized as one of the most effective technology to achieve the goal. Using lightweight materials such as aluminium instead of steel to form steel-aluminum composite structure not only ensures the safety of the vehicle, but also reduces automobile quality, which is widely used in the automotive manufacturing industry due to the advantages of corrosion resistance and high strength. However, the dissimilar joining of aluminium to steel is faced with many difficulties because of the great difference in physical properties (melting point, thermal conductivity, coefficient of linear expansion and so on). Especially, the little solid solubility of iron into the aluminum according to the Al–Fe phase diagram leads to the formation of a series of brittle intermetallic phases that deteriorates the mechanical properties of welded joint by forming cracks.

So the joining aluminium to steel is an urgent problem and hot issues of research. The welding methods can be synoptically divided into solid state bonding, fusion welding and brazing. Y. C Chen et al. joined 6144-T4 aluminum alloy and DC04 low carbon steel sheet by abrasion circle friction stir spot welding, which can get a high quality joint within shorter welding time, and proved that the solid state nature of the process and rapid weld cycle resulted in no intermetallic reaction layer. S. Kundu et al. joined interstitial free steel and commercially pure aluminum by friction stir welding. It was found that the interface layer was consisted of Al3Fe intermetallic compounds and the micro-hardness of interface layer was greater than base metals. The increase of tool rotating speed means the higher heat input generated by the high rotating tool shoulder, which results in the increase of the thickness of interface layer. G. Sierra et al. joined 1.2 mm thick DC 04 low-carbon zinc-coated steel sheet and 1 mm thick aluminium sheet in an overlap configuration by laser welding and gas tungsten arc welding (GTAW). The experiment suggested that tongue-like structure Fe2Al5 phase appeared in the interfacial layer for laser assemblies and complex FeAlSiZn phases were produced in the interfacial layer for GTAW assemblies. Besides, it also pointed that using flux can increase the wetting angles and decrease the reaction layer thickness for laser assemblies. H. T. Zhang et al. joined galvanized steel and 1 060 pure Al by modified MIG welding-brazing process. It was found that the morphology of interface layer changed from ser-
Table 1. Chemical compositions of base metals (wt.%).

<table>
<thead>
<tr>
<th>Materials</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Mg</th>
<th>Cu</th>
<th>S</th>
<th>P</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel</td>
<td>≥0.23</td>
<td>3.00</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>≤0.015</td>
<td>≤0.040</td>
<td>≥0.010</td>
</tr>
<tr>
<td>5A06</td>
<td>–</td>
<td>0.17</td>
<td>0.72</td>
<td>6.25</td>
<td>0.04</td>
<td>–</td>
<td>–</td>
<td>0.21</td>
</tr>
<tr>
<td>Remainder</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Remainder</td>
</tr>
</tbody>
</table>

Table 2. Chemical compositions of welding wires (wt.%).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Zr</th>
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</thead>
<tbody>
<tr>
<td>ER4043</td>
<td>–</td>
<td>–</td>
<td>≤0.05</td>
<td>≤0.05</td>
<td>≤0.05</td>
<td>≤0.001</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>0.20</td>
<td>0.30</td>
<td>5.80–6.80</td>
<td>0.20–0.40</td>
<td>0.20–0.40</td>
<td>–</td>
<td>0.10</td>
<td>0.10–0.20</td>
<td>0.10–0.20</td>
</tr>
<tr>
<td>ER2319</td>
<td>–</td>
<td>0.04</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Bal.</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>0.2 –</td>
<td>–</td>
<td>–</td>
<td>3.00</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 3. Mechanical properties of base metals.

<table>
<thead>
<tr>
<th>Base metals</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5A06 aluminum</td>
<td>≥160</td>
<td>350</td>
<td>≥12.0</td>
</tr>
<tr>
<td>1180DP steel</td>
<td>≥820</td>
<td>≥1 180</td>
<td>≥3</td>
</tr>
</tbody>
</table>

Keller reagent to prepare metallographic samples. Optical microscope (OM, OLYMPUS-PMG3) and scanning electron microscope (SEM, ISM-5310) were used to investigate the microstructures of the joints. The chemical and phase compositions of interface layer and weld were examined by energy dispersive spectrometer (EDS, Link-ISIS), X-ray micro-diffraction (XRD, Discover with GADDS) and transmission electron microscope (TEM, JEM-2100F). Vickers microhardness profiles of weld joints were measured at the load of 100 g and the duration time of 10 s. MTS 810 material test system was used to measure the tensile strength of steel-aluminum joints, which was based on the average of three measurements per condition. Finally, the fracture surfaces of weld joints were studied by SEM.

3. Results and Discussion

3.1. Joint Microstructures

The microstructural characteristics of plasma arc welded joints of DP1180 ultra-high strength steel and 5A06 aluminum alloy were studied by using Al–Cu and Al–Si filler wires respectively. Figure 2 shows the cross-sectional macrostructure and microstructure of the steel-aluminum joint produced with Al–Cu filler wire. From Fig. 2(a), it can be seen that the joint consists mainly of weld zone (WZ), bond zone (BZ) and interface zone (IZ). The WZ is formed
by the solidification of the weld pool which is composed of molten aluminum base metal and filler wire heated by the plasma arc. The BZ is a transition area between the weld and aluminum base metal. The IZ is located at the interface of the weld and steel base metal, a transition area between them. Owing to great difference of melting temperatures between steel and aluminum, during plasma arc welding the aluminum alloy base metal and filler wire melted to form weld pool while the ultra-high strength steel remained solid state. The aluminum was joined to steel by means of the atom diffusion and the steel/aluminum interface reaction. Therefore, the plasma arc welded joint has characteristics of welding-brazing. Figures 2(b) and 2(c) show microstructures of bond zone and weld zone, respectively. As can be seen, the weld has a good metallurgical bond with aluminum base metal without welding defects such as lack of fusion and crack in the bond zone. The aluminum weld pool solidified epitaxially from aluminum base metal grains and $\alpha$-Al cellular crystals tended to grow in the direction perpendicular to the fusion line (Fig. 2(b)), because it is the direction of the maximum temperature gradient and hence maximum heat extraction. With the further advance of solid/liquid interface toward to the weld pool center, the solidification mode changed from cellular crystal to cellular dendrite, and finally to dendrite (Fig. 2(c)), which is mainly attributed to the constitutional supercooling degree continuing to increase due to the temperature gradient decreasing and the concentration of solute (Cu) increasing in the pool. From XRD result shown in Fig. 2(d), the weld zone consists mainly of $\alpha$-Al solid solution and $\mathrm{Al}_2\mathrm{Cu}$ intermetallic compound. Figures 2(e) and 2(f) present SEM image and EDS analysis result of weld zone respectively. The white phase was observed between $\alpha$-Al grains (Fig. 2(e)), its composition was 76.92at.%Al and 23.08at.%Cu (Fig. 2(f)), and hence the white phase at the $\alpha$-Al grain boundaries was identified as $\mathrm{Al}_2\mathrm{Cu}$ intermetallic compound. During the solidification of weld pool, with the growth of $\alpha$-Al grains the solute Cu was rejected into the liquid between $\alpha$-Al grains, raising Cu concentration and finally precipitating $\mathrm{Al}_2\mathrm{Cu}$ intermetallic at $\alpha$-Al grain boundaries.

Figure 3 illustrates microstructures, EDS line-scan and XRD results of interface zone using Al–Cu filler wire. There exists an interface layer between aluminum weld and steel base metal. The interface layer displays a fine needle-like structure at the aluminum weld side and a tongue-like structure at the steel base metal side, as shown in Fig. 3(a). According to EDS line-scan results shown in Fig. 3(b), the distribution of Fe and Al is heterogeneous in the interface layer. From aluminum side to steel side, the Fe concentration increased and the Al concentration decreased, indicating that the inter-diffusion of Fe and Al atoms across the interface occurred during plasma arc welding. The chemical compositions of the needle-like phase and tongue-like phase are 78.27at.%Al+20.48at.%Fe+...
1.25 at.% Cu and 73.70 at.% Al + 25.63 at.% Fe + 0.67 at.% Cu. Figure 3(c) shows Micro-XRD result of the interface layer. The Fe2Al5 and Fe4Al13 phases were detected in the interface layer, demonstrating that the steel/aluminum interface reaction occurred to form Fe–Al intermetallic compounds (IMCs). It should be pointed out that the XRD result is not sufficient because the data to indicate Fe4Al13 overlapped that of Fe2Al5. TEM was used to reveal the phase composition of the interface layer. Figure 3(d) illustrates TEM bright field image. Figures 3(e) and 3(f) are the diffraction patterns of tongue-like phase and needle-like phase, respectively. The results of diffraction patterns show that the tongue-like phase is Fe2Al5 which has an orthorhombic unit cell with a=0.7649 nm, b=0.6413 nm, c=0.4216 nm, and the needle-like phase has a monoclinic unit cell with a=1.5489 nm, b=0.8083 nm, c=1.2476 and β=107.5°. According to references,22–24) Fe4Al13 has a monoclinic unit cell with a=1.5489 nm, b=0.8083 nm, c=1.2476 and β=107.72°, and FeAl3 unit cell is with a=1.549 nm, b=0.808 nm, c=1.248 and β=107.75°. The crystal lattice parameters of needle-like phase are closer to that of Fe4Al13. Thus, the needle-like phase is identified to be Fe4Al13. From Fe–Al phase diagram, FeAl3 phase similar to Fe4Al13 is formed under the condition of thermodynamic equilibrium. Under nonequilibrium conditions the formation of Fe–Al intermetallic compounds is controlled by not only the thermodynamic factors but also the kinetic factors such as the reaction temperature, hold time and so on.25–28) Plasma arc welding is an extremely nonequilibrium process, thus the formation of needle-like Fe4Al13 in the interface layer is related to the high interface reaction temperature, short hold time and fast cooling rate. According to results above, it can be demonstrated that the interface zone consists mainly of Fe2Al5 and Fe4Al13 intermetallic compounds, the tongue-like Fe2Al5 layer at steel base metal side (Fig. 3(e)) and needle-like Fe4Al13 layer at aluminum weld side (Fig. 3(f)). In addition, from Figs. 3(a) and 3(d) the epitaxial growth in the interface zone is also evident, the needle-like Fe4Al13 crystals growing epitaxially from the Fe2Al5 grains to aluminum weld.

Figure 4 shows microstructures, XRD and EDS results of plasma arc welded joint of ultra-high strength steel and aluminum alloy using Al–Si filler wire. The experimental results indicated that the macrostructure of steel-aluminum joint produced with Al–Si filler wire is similar to that with Al–Cu filler wire, including weld zone (WZ), bond zone (BZ) and interface zone (IZ). The weld consists mainly of α-Al and Si phases, as shown in Figs. 4(a) and 4(b). During plasma arc welding, the inter-diffusion of Fe and Al atoms and interface reaction occurred to form the interface layer, the tongue-like phase at steel side and needle-like phase at the aluminum side, as shown in Fig. 4(c). EDS analysis results indicated that the atom percents of the tongue-like phase and needle-like phase are 70.36 at.% Al +
20.29 at.%Fe + 9.35 at.%Si and 73.70 at.%Al + 25.63 at.%Fe + 0.67 at.%Si, corresponding to Fe$_2$Al$_5$ and Fe$_4$Al$_{13}$ phases, respectively.

Based on results above, it is concluded that the steel/aluminum interface reaction dependent on inter-diffusion of Fe and Al is necessary for joining of steel and aluminum. The microstructure evolution process of the interface zone during plasma arc welding can be summarized as follows:

1. The initial stage: Under the action of plasma arc, the aluminum base metal and filler metal melted to form aluminum pool while the steel base metal remained solid state. The liquid aluminum wetted and spread on the solid steel surface, Fe atoms diffused into liquid aluminum pool and Al atoms diffused into solid steel. The diffusion rate of Al atom in the solid steel was much smaller than that of Fe atom in the liquid aluminum due to it needing higher diffusion activation energy, and hence Al atoms accumulated easily at the edge of the steel, as shown in Fig. 5(a).

2. The Fe$_2$Al$_5$ nucleation stage: with the increase of Al concentration at the edge of the steel, the supersaturated solid solution formed firstly at the interface and it transformed into Fe$_2$Al$_5$ nucleus when the ratio of Fe and Al atoms reached about 2/3, as shown in Fig. 5(b).

3. The Fe$_2$Al$_5$ layer formation stage: with incessant inter-diffusion of Fe and Al atoms, the Fe$_2$Al$_5$ nuclei grew and the neighboring nuclei were connected together to form

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**Fig. 4.** Microstructures and XRD results of welded joint using Al–Si welding wire: (a) weld microstructure, (b) weld XRD, (c) interface microstructure, (d) EDS result.

**Fig. 5.** The microstructure evolution process of interface zone: (a) initial stage, (b) Fe$_2$Al$_5$ nucleation stage, (c) Fe$_2$Al$_5$ layer formation stage, (d) Fe$_4$Al$_{13}$ layer formation stage.
3.2. Effects of Welding Conditions

The welding conditions are important factors affecting the welding quality and joint properties. Effects of welding conditions on dissimilar plasma arc welding of DP1180 ultra-high strength steel and 5A06 aluminum alloy were studied by changing groove geometry, welding parameter and filler wire composition.

3.2.1. Effects of Groove Geometry

Figure 6 shows the weld appearance produced in various groove geometry (groove A, B and C). When the groove A with bevel angle of 30° and 45° on aluminum and steel sheets respectively was used, the weld had a bad appearance and the incomplete joining defect appeared at weld top just adjacent to the steel bevel (Fig. 6(a)), which deteriorates not only the weld appearance but also the mechanical properties of the steel-aluminum joint. It can be explained by large bevel angle (30°) on the aluminum sheet affecting the spreading of molten aluminum on steel bevel. When the bevel angle on the aluminum sheet was decreased to 0° (groove B), a single bevel groove, the incomplete joining defect disappeared in the joint and the weld appearance was improved obviously, as shown in Fig. 6(b). The groove C was also used for dissimilar plasma arc welding of steel and aluminum. The result indicated that the weld appearance can be also improved by using the grooves C, but it resulted in excessive fusion ratio, which is unfavorable for improving the joint microstructure and property by changing the filler wire composition.

These results indicated that the groove geometry had an obvious effect on the appearance of weld. It is more favorable to use the single bevel groove (groove B) for improving the welding quality of steel and aluminum. Under the condition of groove B, the effects of welding parameter and filler wire composition were studied in this experiment.

3.2.2. Effects of Welding Parameter and Filler Wire Composition

According to microstructure characteristics of plasma arc welded joint, the interface zone should be the weakest zone in the steel-aluminum joint because it consists mainly of hard and brittle Fe–Al intermetallics (Fe2Al5 and Fe4Al13). The experimental results indicated that the welding parameter (welding current) and filler wire composition (Al–Cu and Al–Si) had great effect on the interface layer. Figures 7 and 8 show the interface layers produced with different welding currents using Al–Cu and Al–Si filler wires, respectively. When the welding current was 80 A, the interface layer was thin and discontinuous, and the incomplete jointing defect and crack were observed in the interface, as shown in Figs. 7(a) and 8(a). With the increase of welding current, the thickness of interface layer increased, the incomplete jointing defect decreased and finally the continuous interface layer formed (Figs. 7(b), 7(c) and 8(b), 8(c)). When the welding current exceeded 100 A, the crack appeared in the interface layer, as shown in Figs. 7(d) and 8(d). The effect of welding current on the interface layer is mainly related to changing welding heat input. The welding heat input (E) represents the amount of heat input per unit length of weld, and is determined according

\[ E = \frac{\eta IU}{v} \]  

where I is the welding current, U is the arc voltage, v is the welding speed, and \( \eta \) is the heat source efficiency.

The relatively low welding current (80 A) generated relatively low heat input, peak temperature of weld thermal cycle and interface reaction temperature, which results in decreasing the diffusion rate of Fe and Al atoms and the insufficient steel/aluminum interface reaction, and hence forms thin and discontinuous interface layer with the incomplete jointing defect. The joining defect not only decreased the effective joining area but also produced the stress concentration at its tip, promoting the nucleation and propagation of crack in the interface. With the increase of welding current, the heat input, the peak temperature and reaction time of steel/aluminum interface increased, resulting in accelerating the inter-diffusion of atoms and growth of the interface layer. The excessive heat input increasing the crack susceptibility is mainly attributed to increasing brittle Fe–Al intermetallic compounds in the interface zone and tensile stress in the joint. It is noted that the crack propagated mainly along the Fe2Al5 layer close to the steel...
indicating that the Fe$_2$Al$_5$ layer is more brittle than Fe$_4$Al$_{13}$ layer.

From Fig. 9, it can be seen that the filler wire composition has an obvious effect on the thickness of interface layer. With the increase of welding current from 80 A to 110 A, the interface layer thickness with Al–Si and Al–Cu filler wires increased from 3.9 $\mu$m to 13.8 $\mu$m and from 3.7 $\mu$m to 8.6 $\mu$m, respectively. The interface layer thickness with Al–Cu filler wire is smaller than that with Al–Si filler wire, which is mainly related to Cu affecting the inter-diffusion of Fe and Al atoms. During plasma arc welding, Fe atoms diffused into liquid weld pool, Al and Cu atoms diffused into solid steel and Fe$_2$Al$_5$ formed at steel/aluminum interface firstly. Due to the strong binding force between Cu atom and the surface of Fe$_2$Al$_5$ crystal, Cu atoms accumulated (Figs. 7(d) and 8(d)), indicating that the Fe$_2$Al$_5$ layer is more brittle than Fe$_4$Al$_{13}$ layer.

Fig. 7. The morphology of interface layers at different welding currents using Al–Cu filler wire: (a) 80 A, (b) 90 A, (c) 100 A, (d) 110 A.

Fig. 8. The morphology of interface layers at different welding currents using Al–Si filler wire: (a) 80 A, (b) 90 A, (c) 100 A, (d) 110 A.

Fig. 9. Effect of welding current on interface layer thickness using Al–Cu and Al–Si filler wires respectively.
and deposited smoothly on the surface of Fe$_2$Al$_5$ crystal to block the inter-diffusion of Fe and Al atoms and to restrain the growth of Fe–Al intermetallics in the preferred orientation.

The experimental results indicated that the welding current and filler wire composition had great effect on the microhardness and tensile strength of plasma arc welded joints of DP1180 ultra-high strength steel and 5A06 aluminum alloy. Figure 10 shows the microhardness distribution across the steel-aluminum joints produced with Al–Cu and Al–Si filler wires respectively. The change of joint microhardness is very obvious. The average hardness of 5A06 aluminum alloy and DP1180 steel base metals were 69.5 HV and 212.6 HV, respectively. The hardness of aluminum alloy welds (71.6 HV–98.4 HV) was higher than that of the aluminum base metal (69.5 HV). The highest hardness values of the joints appeared in the interface zones consisting of Fe–Al intermetallics. The filler wire composition has effect on the hardness of interface zone. With the Al–Si filler wire, the average hardness of interface zone was 433.6 HV. It was decreased to 405.2 HV when the Al–Cu filler wire was used, which is related to forming (Fe, Cu)$_2$Al$_{13}$ and (Fe, Cu)$_2$Al$_5$ intermetallics lowering hardness brittleness and of interface zone.

Figure 11 shows the effect of welding current and filler wire composition on the tensile strength of steel-aluminum joints and the fracture surface morphology of the joints. From Figs. 11(a) and 11(b) it can be seen that the low
welding current (80 A) deteriorates the joint tensile strength (34–45 MP), which is mainly attributed to the discontinuous interface layer with incomplete joining and crack defects decreasing the effective joining area and promoting the propagation of crack under tensile stress. The maximum tensile strength of joints with Al–Si and Al–Cu filler wires reached 62 MPa and 118 MPa respectively at welding current of 90 A due to forming continuous interface layer. With further increase of welding current, the joint strength lowered and it decreased to 45 MPa (Al–Si filler wire) and 90 MPa (Al–Cu filler wire) when the welding current was increased to 110 A. It can be explained by forming excessive Fe–Al intermetallics and cracks in the interface zones. The experimental results indicated that the joint fracture mainly occurred at the interface zone, demonstrating that the interface intermetallic layer is the weakest region in the plasma arc welded joints of DP1180 ultra-high strength steel and 5A06 aluminum alloy. Figures 11(c) and 11(d) illustrate the fracture surface morphology of steel-aluminum joints with Al–Si and Al–Cu filler wires respectively. The joint fracture surface with Al–Si filler wire is flat, and exhibits brittle fracture characteristics, as shown in Fig. 11(c). In addition, the micro-cracks were observed on the fracture surface. From Fig. 11(d) it can be seen that the joint fracture surface with Al–Cu filler wire is different from that with Al–Si filler wire. There is not the micro-crack on the fracture surface and some plastic deformation features are observed, indicating that the formed (Fe, Cu)4Al13 and (Fe, Cu)2Al5 in the interface zone lower not only its hardness but also its brittleness. Based on results above, it is favorable to use Al–Cu filler wire with the welding current of 90 A for improving the joint strength of DP1180 ultra-high strength steel and 5A06 aluminum alloy.

4. Conclusions

(1) The steel-aluminum joint has characteristics of welding-brazing and can be divided into weld zone, bond zone, and interface zone. The weld pool solidifies epitaxially from aluminum base metal and the solidification mode changes from α-Al cellular crystal to cellular dendrite, and finally to dendrite due to the constitutional supercooling degree continuing to increase. The interface reaction dependent on inter-diffusion of Fe and Al is necessary for joining of steel and aluminum, the tongue-like Fe2Al3 layer forming at steel side firstly and then the needle-like Fe2Al13 crystals growing epitaxially from the Fe2Al3 grains to aluminum weld. The interface layer is the weakest region in the joint due to brittle Fe–Al intermetallics (IMCs).

(2) The welding current and filler wire composition have great effect on the interface IMC layer. With the increase of welding current, the interface layer thickness increases, which is mainly associated with increasing the heat input and interface reaction temperature to accelerate the inter-diffusion of Fe and Al. The large welding current results in increasing the crack susceptibility due to forming excessive IMCs in the interface and tensile stress in the joint. Owing to Cu restraining the growth of interface IMC layer, with Al–Cu filler wire the interface layer thickness has a decreased tendency

(3) The interface zone is an important factor affecting the mechanical properties of steel-aluminum joints. The interface zone has the highest hardness in the joints due to it including hard Fe–Al IMCs. The joint strength can be improved by forming the continuous interface layer, but excessive IMCs in interface zone deteriorate the joint strength. The joint strength with Al–Si and Al–Cu filler wires can reach 62 MPa and 118 MPa, respectively. The joint with Al–Cu filler wire having higher tensile strength is related to the Cu restraining the growth of interface IMC layer and lowering its hardness and brittleness. It is favorable to use Al–Cu filler wire with the welding current of 90 A for improving the joint strength of DP1180 ultra-high strength steel and 5A06 aluminum alloy.

Acknowledgments
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