Effect of different coatings on the weldability of Al to steel

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Abstract. The influence of different coatings on the weldability of Al/steel was assessed in this study. Different kinds of the coatings, which included pure zinc coating, Fe-Zn coating and without coating, were considered. The thickness of the coating was also studied. Different configuration of overlap and butt joint was used, and different welding methods including cold metal transfer (CMT) welding-brazing and laser welding-brazing with filler metal were investigated. Samples were fabricated and the weld appearance, microstructure and composition analyses of the joints were examined. It was found that the Al to steel without coating could not be welded due to the formation of large amount of brittle Fe-Al intermetallic compounds (IMC). The coating helped suppress the formation of IMC and a welding-brazing joint was produced. However, pure Zn coating enhanced the wetting of molten filler onto the solid steel substrate, but Fe-Zn coating barely enhanced the molten filler to wet the steel substrate. The coating with a thickness of 10-20 µm contributed to a better performance of Al/steel joint.

1. Introduction
Effective joining between Al alloy and steel has become an attractive issue in the manufacturing industry. However, the joining of aluminium to steel is a great challenge because of the large differences in thermo-physical properties between the two materials and especially the excessive formation of brittle Al-Fe at elevated temperatures [1-5], which could degrade the joint greatly. In order to suppress the large formation of Fe-Al IMC, solid-state welding methods have been tried to join these dissimilar metals joints. Though the IMC could be hindered using these processes, high efficiency is still lacking, and the shape and size of such solid-state joints are restricted. The welding-brazing method have been proposed based on the huge difference in melting points of Al (649°C) and iron (1539°C) and the brittle Fe-Al IMC could be restricted by only melting aluminium alloy. Arc welding-brazing [6-9] and laser welding-brazing [10-14] had been used to connect Al and steel successfully. These studies have found that the coating has a crucial effect on joining Al to steel. Thus, it is necessary to join aluminium to steel with various coatings. The purpose of this study was the investigation of different coatings on the weldability of Al to steel.

2. Experiment
For the overlap joint of Al steel, 1 mm thick aluminum Al6061 and 1.5 mm thick bare, galvanized and galvannealed steel were used. Al4043 filler wire with a diameter of 1.2 mm was also used in this study. The CMT method was used to join Al/steel in overlap joint. The Al6061-T6 workpiece was placed on top of the steel workpiece in a lap configuration with an overlap distance of 10 mm. The angle between the welding torch and the normal to the lap seam was 45 degrees away from the direction of welding. The welding direction was parallel to the lap seam and was offset from the edge of the Al sheet edge. A 100% argon shielding gas with a flow rate of 15 L/min was used throughout the experiments.

For the butt joint of Al steel, 3 mm thick aluminum Al6061 and 3 mm thick bare and galvanized steels were used. The groove of the joint was in the pattern “V”. The steel was coated with a pure zinc coating with different thickness for the galvanized before welding. Laser welding was performed by a fiber laser. The wire feeder was produced by Fronius. During welding process, the filler wire was fed in the leading edge of the molten, and the wire feed angle was adjusted to 30° to the sheet plane. The laser beam was tilted 12° ahead, i.e. in trailing position, and the laser focus was adjusted to 20 mm above the surface of the workpiece. Shielding argon gas was adopted at double sides of workpiece to avoid oxidation of weld metal, and a flow rate of 20 L/min and 5 L/min was used to protect the surface and bottom of the molten zone respectively.

To analyze the quality of Al/steel joint by laser welding-brazing process, the cross-sections of the specimens were prepared and examined. The polished Al/steel joint was etched by Dix-Keller solution. The microstructures of the weld were observed by scanning electron microscope equipped with an energy-dispersive X-ray spectrometer.

3. Results and Discussions

3.1. Effects of different coatings on the weld appearance and microstructure of Al/steel

To assess the effect of zinc coating on the weldability between Al and steel, weld appearance and microstructure of Al to bare steel were examined first. Both the overlap joint and the butt joint were displayed in Figure 1, and the microstructure of overlap joint was also included. As seen, the weld appearance was very bad for the overlap joint, and the crack was found from the top surface. It fully spreaded on the steel substrate, but the weld metal covered barely on the aluminum substrate. It was primarily attributed to the combination of strong affinity of aluminum-steel and melting of aluminum substrate. Because enthalpy of mixing of aluminum in iron (i.e., -48 kJ/mole) was less than that of aluminum in aluminum (i.e., 0 kJ/mole), affinity of aluminum in aluminum was weaker than that of Al in Fe. The appearance of the butt joint was also very poor, and the crack was produced between the weld metal and the steel, leading to the split of the weld immediately after welding. the macroscopic and microscopic of the overlap joint were shown in Figure 1. As seen, massive lath-shaped Fe-Al IMC, which is very brittle, was formed in the weld metal. The observations showed that significant amount of steel was melted under an intensive arc heat. The molten steel reacted with aluminum filler metal, leading to formation of a large amount of brittle Fe-Al IMC. These results suggested that the cracks observed in the weld metal were likely resulted from the combination of the formation of brittle Fe-Al IMC and thermal induced residual stresses due to the difference in coefficient of thermal expansion between steel and aluminum. According to the results, it could not join Al to steel directly using the fusion methods, whatever the CMT weld or the laser filler weld process.
Figure 1. Weld appearance and microstructure of Al to bare steel. (a) overlapped joint with CMT welding-brazing; (b) butt joint with laser welding-brazing; (c) the macrostructure of the overlapped joint; (d) the microstructure of the overlapped joint

Figure 2 presented the results of CMT overlap welding of Al to galvannealed steel. The galvannealed zinc coating, the deposited filler metal on the steel surface, the weld appearance of Al/steel, and the microstructure of the joint were shown in the figure. As observed, the 10μm thickness coating was mainly composed of Fe-Zn IMC using line map and XRD analysis. The filler metal could not wet properly the steel surface by observing the deposited weld metal, and the weld bead of Al/steel was discontinuous and sporadic. The molten aluminum didn’t wet well the steel substrates, and the wetting angle between the weld metal and the steel was about 115°. Further analysis of the overall interface between the weld metal and the steel was very poor. According to line map analysis of the interface at the zone A, the acceptable bonding interface, which consisted of Fe-Al IMC with a thickness of ~5μm, was formed at this zone. However, severe cracks were observed between the weld metal and steel at zone B, and the galvannealed zinc coating was still existed after welding. The melting points of Fe-Zn coating was ~950°C. It was not fully molten due to its high melting point, and consequently hindered the wetting of the molten filler metal on the steel substrate. As a result, the welds with poor quality were produced.

Figure 3 presented the results of CMT overlap welding of Al to galvanized steel. The galvanized zinc coating, the weld appearance of Al/steel, and the microstructure of the joint were shown. As observed, the 10μm thickness coating was mainly composed of Zn solid solutions using line map and XRD analysis. The results showed that adequate wetting of the molten filler on the substrate, and sound Al/steel weld bead was achieved. A welding-brazing interface of Fe-Al IMC was obtained, which was homogeneous continuous with a thickness of 2-5 μm. No zinc coating maintained at the interface after welding. Because the melting points of pure Zn coatings was 400°C, and it was readily melted under the CMT arc, and the filler metal spreaded on liquid zinc layer other than the surface of solid steel substrate, which improved the wettability and spreadability of the molten weld metal.
Figure 2. Weld appearance and microstructure of Al to galvannealed steel with CMT welding-brazing. (a) the coating; (b) line analysis of the coating; (c) XRD analysis of the coating; (d) deposited metal; (e) weld appearance; (f) the joint; (g) zone A; (h) line analysis of the interface; (i) zone B

Figure 3. Weld appearance and microstructure of Al to galvanized steel CMT welding-brazing. Weld appearance and microstructure of Al to galvannealed steel. (a) the coating; (b) line analysis of the coating; (c) XRD analysis of the coating; (d) weld appearance; (e) the joint; (f) the interface; (h) line analysis of the interface
The butt joint split immediately after welding for the Al to bare steel in Figure 1, but sound bead was obtained for the Al to galvanized steel in Figure 3. Thus, the steel sheet was treated with a galvanized process to obtain a zinc-coating on the groove face before welding. Then butt joining of Al/steel was done with a laser welding process. The zinc coating with different thickness of 100 µm and 20 µm was used. The appearance and microstructure was shown in Figure 4. As seen, it is feasible to join aluminum alloy to steel in butt joints, and good appearance can be obtained with both coating. The microstructure of the joint with 100µm coating showed that large amount of zinc was retained after welding, which decreased the joint strength greatly. However, the interface for the joint with 20 µm coating displayed similarity with the interface in Figure 3, and a thin Fe-Al IMC was produced. This joint showed much higher strength than the former. Thus, though the zinc layer helped the wettability and spreadability of filler metal on the steel surface, but the thickness of the coating need to be controlled.

![Figure 4](image)

**Figure 4.** Weld appearance and microstructure of Al to galvanized steel with coating in different thickness using laser butt joining process. (a) the thick coating; (b) weld appearance; (c) weld joint; (d) interface of Al to steel with thick coating; (a) the thin coating; (b) weld appearance; (c) weld joint; (d) interface of Al to steel with thin coating

4. Conclusions

The effect of different coatings on the joining of Al to steel has been investigated. CMT welding-brazing and laser welding-brazing methods were used in this study. It was found that zinc coating on steel substrate is essential. The effective joint could not be obtained due to the formation of large amount of brittle Fe-Al IMC. Fe-Zn coating of galvannealed steel was barely molten during welding process due to its high melting point, and consequently it barely enhanced the molten aluminum filler to wet the steel substrate. Pure Zn coating on galvanized boron steel was molten, and it enhanced the wetting of molten aluminium filler onto the solid steel substrate. Consequently, the welds with smooth appearance and low reinforcement were produced. The thickness of coating also had a great influence on the weldability of Al/steel and the coating with a thickness of 10-20 µm contributed to a higher joint strength.

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