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Role of zinc layer in resistance spot welding of aluminium to steel

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ABSTRACT

Effects of zinc layer on microstructure and mechanical behavior of resistance spot welds of aluminum to galvanized (GS-Al joint) and low carbon steel (PS-Al joint) were explored. The results showed that although nugget 'volume' in PS-Al joint was larger, the nugget 'diameters' of PS-Al and GS-Al joints were almost the same in size since the melted zinc layer was pushed toward the outer regions of the nugget. Melting and evaporation of zinc coat led to reduction of Al-Fe intermetallic layer thickness. Presence of zinc also reduced the fixture-induced tensile stress. Utilizing carbon steel fixtures during welding caused a sensible vibration in the joint members. The vibration resulted in fragmentation and decrease of the intermetallic compounds at the joint interface. Moreover, while PS-Al joints showed higher strength than that of GS-Al ones at the welding currents <12 kA, fracture load of GS-Al welds exceeded PS-Al joints beyond 12 kA. Low welding current resulted in an incomplete joint at GS-Al welds. However, lower induced tensile stress, as well as the formation of intermetallic layer with the thickness smaller than the critical value (~5.5 μm) in GS-Al joints, led to superior mechanical properties at high welding currents.

1. Introduction

Because of suitable mechanical properties and low cost of steel as well as aluminium low density and high corrosion resistance, steel/aluminium bimetallic parts can be applicable in various industries such as automotive and aerospace. However, joining between aluminium alloys and steels by fusion welding methods faces to technological and metallurgical limitations. Significant difference between their melting point and thermal conductivity as well as the formation of brittle intermetallic compounds (IMCs) such as Fe_2Al_5 and $FeAl_3$ at the joint interface are some obstacles resulting in low quality welds [1–6]. Moreover, difference between aluminium and steel thermal expansion coefficients and specific heats leads to high residual stress at the joint region. The residual stress and simultaneous presence of brittle IMC layer at the joint interface may result in cracking inside the weld zone [7]. Resistance spot welding (RSW) is a commonly used process in welding of car bodies and therefore, some research works have been conducted on the RSW of aluminium alloys to steel sheets.

Qiu et al. [8–11] tried to improve the quality of Al-5052/SPCC dissimilar resistance spot welds by a SPCC steel cover plate placed on the aluminium sheet. Use of cover plate resulted in generation of more heat at the aluminium side of the joint and thus made RSW of aluminium alloy and steel possible under relatively low welding currents. They reported that the IMC layer thickness, nugget diameter and ultimate shear-tensile load increased with raising the welding current. Despite the steel sheet, aluminium was melted during the passage of the electrical current. A continuous Al/Fe IMC layer was formed with the maximum thickness at the central region of the weld nugget. They related variation in IMC thickness to the temperature distribution at the welded region, where the central region experienced the highest temperature [8]. The IMC layer at the central region consisted of two layers. One layer identified as $FeAl_3$ and formed next to the aluminium base sheet had needle-like morphology and the other one, Fe_2Al_5, was tongue-like orientated toward the steel base metal. Oikawa et al. [12] utilized an aluminium clad steel sheet between Al-5·5Mg aluminium alloy and EDDQ steel in order to decrease reactions between the base sheets. Their results showed that a defect-free joint formed and the strength of the joint improved using the transition material. Sun et al. [13] applied a similar approach to Oikawa et al. [12] for RSW of 1.4 mm SAE1008 mild steel sheet to 2 mm 5182-O aluminium alloy sheet. Zhang et al. [14] worked on RSW of galvanized high strength steel and 6008-T66 aluminium alloy. They reported that two intermetallic phases of Fe_2Al_5 and Fe_4A1_{13} ($FeAl_3$), both containing Zn, were formed at the joint interface with tongue-like and needle-like morphologies, respectively. They did not investigate the effects of Zn on the interfacial microstructure and joint strength. Since, zinc interlayer may improve the joint properties by forming a good metallurgical bond at the weld interface [15], there are a few studies which have investigated the effect of zinc layer on the properties of the joints made using other fusion welding processes rather than RSW. For instance, Ma et al. [16] investigated joining of galvanized high strength steel to aluminium using two-pass laser welding. They mentioned that Zn interlayer resulted in thinner Al-rich IMC layers at the weld zone and improved mechanical properties of

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the welds. Their results also showed that a part of aluminium at the weld zone dissolved in zinc and the remaining aluminium formed Fe-rich IMCs with suitable toughness and mechanical properties [16].

Therefore, presence of zinc layer may affect the characteristics of the Al/steel resistance spot joints; little work has been performed on this field. Therefore, the present work aims to investigate the role of zinc layer in RSW of aluminium to steel through comparison of microstructures and mechanical properties of the resistance spot welds between aluminium and low carbon as well as galvanized steels.

2. Experimental procedures

Al-5052, St-12 (DC 01) and low carbon galvanized (ASTM A653 CS-Type B-G60) sheets with the thicknesses of 2, 1 and 1 mm, respectively, were used in the present study as the base materials. The zinc coat layer on the galvanized steel was pure zinc (>99 wt.% Zn) with the thickness of ~10 μm. The mechanical properties of the base sheets are given in Table 1. The Chemical compositions of Al-5052 and steel sheets are given in Table 2. The sheets were cut into the dimensions of 105 mm × 45 mm and the overlap length was set to 35 mm (Fig. 1-a) according to AWS D8.9 standard [17]. Acetone was used to clean the surfaces of the sheets before welding. All the specimens were prevented from distortion during welding by a carbon steel fixture (ferromagnetic material) shown in Fig. 1-b. In order to investigate the effect of the magnetic properties of the fixture on the formation of vibration during welding, the same fixture was prepared from austenitic stainless steel (nonmagnetic material) and used. Al-5052 sheets were completely fixed on the steel sheets using the fixture before welding in a configuration that Al-5052 sheets were placed on top of the steel sheets during welding. For RSW of the samples, copper electrodes with the diameter of 6 mm were used. The pre-squeeze time, welding current, welding time, post-weld holding time and electrode force were 50 cycles, 9–14 kA, 20 cycles, 20 cycles and 3 kN, respectively. Alternating current (AC) was used for welding the specimens. It should be mentioned that no weld nugget formed at welding current <9 kA. Welding currents >14 kA were also not applicable because of sever expulsion and the welding equipment limitation. A nomenclature system shown in Table 3 was used to simplify naming the specimens.

The imposed stress due to application of the fixture during welding (Fig. 1-b) was evaluated by measurement of the distortion of the base sheets after welding with and without fixture. To this end, aluminium sheets with the dimensions of 200 mm × 50 mm were placed on the steel sheets (galvanized and low carbon steel) with the same size and a spot weld was made at the center of the samples for each of the joints. After welding, the obtained distance between the aluminium and steel sheets at the end of the joints was measured as a criterion for distortion.

Mechanical strength of the joints was investigated by shear-tensile and cross-tension tests using an Instron tensile testing machine under the crosshead speed of 5 mm min^{-1}. During the shear-tensile tests, alignment shims were used to reduce the eccentricity of the loading path (Fig. 1-a). As all the specimens fractured with the interfacial mode, medium nugget diameters were measured from the fracture surfaces.

Stereo, optical and field emission scanning electron microscopes (FESEM) equipped with an energy dispersive X-ray spectroscopy (EDS) were used to observe and characterize the microstructures of aluminium and steel sheets as well as the Al/Fe IMCs at the weld zone. The cross-section of the St-12 sheets was etched by 2% Nital etchant solution. The Al sides of the welds were also electro-etched by the Barker etchant solution (2.5 vol% fluoroboric acid in water) and the grain structures were observed by optical microscope under polarized light. In order to investigate crack propagation path during shear-tensile test, cross-sections of the weld nuggets were observed by optical microscope after fracture of the specimens.

Table 1
Ultimate tensile strength (UTS) of the base metals used in this work.

Material	UTS (MPa)	YS (MPa)	Elongation (%)
Al-5052	250	197	11.5
St-12	288	155	42
Galvanized steel	364	273	32

Table 2
Chemical compositions of St-12, galvanized steel and Al-5052 sheets (Wt.%).

Material	Fe	C	Si	Mn	P	S	Cr	Mg	Al
St-12	Base	0.06	0.01	0.23	>0.02	>0.02	–	–	0.05
Galvanized steel	Base	0.05	0.01	0.19	>0.02	>0.02	–	–	0.05
Al-5052	0.23	–	0.12	0.02	–	–	0.14	2.17	Base

3. Results and discussion

3.1. Macro- and microstructural characterization of weld zone

3.1.1. Weld cross-section and nugget diameter

The macroscopic cross-sections of the weld nuggets for both PS-Al-I10 and GS-Al-I10 joints are shown in Fig. 2. As can be seen, while the steel sheet was just affected by the produced heat with no indication of melting, Al-5052 sheet was melted during welding and formed the weld nugget with columnar grains (Fig. 2c and d). Referring to Fig. 2a and b, weld nugget in PS-Al joint had larger *volume* than the one in GS-Al joint. It seems that the welding heat devoted to melting of aluminium in GS-Al joint was lower than that in PS-Al joint due to lower galvanized steel/Al-5052 contact resistance [18] and heat consuming by melting of the zinc coat on the galvanized steel.

Fig. 3-a depicts the nugget diameter variations with welding current. Since weld was not created in GS-Al joint at 9 kA welding current, the nugget diameter of this sample was not presented in Fig. 3-a. Both PS-Al and GS-Al joints showed relatively the same nugget diameter at a given welding current. It should be noted that the terms of *nugget diameter* and *nugget volume* used in this article have different meanings. While nugget volume presents the volume of the melted zone inside the aluminium sheet (as shown by broken lines in Fig. 2-a and b), the nugget diameter is the diameter of the region at the interface of two sheets in which joining occurs. The nugget diameters were measured after fracture of specimens in shear-tensile test as shown in Fig. 3-b and c. It is worth noting that although the nugget volume in PS-Al joint was larger, the nugget diameters of PS-Al and GS-Al joints were relatively the same in size since the melted Zn layer was pushed toward the outer regions of the nugget due to the pressure of the electrodes and subsequently formed the metallurgical bonds between the aluminium and steel sheets. Traces of molten Zn at peripheral region of the nugget in GS-Al joints are shown in Fig. 3-b.

3.1.2. Al-Fe intermetallics

Fig. 4 shows the microstructure of the joint interface in GS-Al-I10 specimen. The welding heat resulted in the formation of IMC layer at the interface of the joints consisting of two distinct layers. The layer with a needle-like morphology formed next to the aluminium alloy is FeAl$_3$ and the tongue-like layer orientated toward the steel is Fe$_2$Al$_5$ [8,19]. Similar intermetallic layers were also observed in PS-Al joints. Effect of welding current on the IMC layer thickness is presented in Fig. 5. In PS-Al joints, IMC layer thickness increased by enhancement of the welding current in such a way that the increasing rate reduced with increase in heat-input. However, in GS-Al joints, intermetallic thickness first increased with enhancement of the welding current up to 12 kA and then decreased beyond it. On the other hand, GS-Al joints had intermetallic layers with lower thickness at almost all welding currents in comparison to PS-Al joints. Increase in intermetallic thickness with welding current was an expected trend since there is a direct relationship between welding current and nugget heat input. However, decreasing trend of the IMC layer thickness in high welding currents