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Optimised design of electrode morphology for novel dissimilar resistance spot welding of aluminium alloy and galvanised high strength steel

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ABSTRACT

A novel resistance spot welding method of dissimilar materials of 6008-T66 aluminium alloy and H220YD galvanised high strength steel was presented, and the morphology of welding electrodes was designed optimally. Macrostructure, microstructure and mechanical property of the welded joints obtained with optimised electrodes were studied. Numerical simulation of current density distribution and temperature field during welding was also performed. The optimised electrodes were a planar circular tip electrode with tip diameter of 10 mm on the steel side and a spherical tip electrode with spherical diameter of 70 mm on the aluminium alloy side. The welded joint obtained with optimised electrodes could be regarded as a special welded-brazed joint, and an intermetallic compound layer composed of Fe_2Al_5 and Fe_4Al_{13} with maximum thickness of about 4.0 μm was formed at the aluminium/steel interface in the welded joint. Tensile shear load up to 5.4 kN was achieved for the welded joint obtained with optimised electrodes. Current density distribution during welding with optimised electrodes was more homogeneous than that with F type electrodes. Furthermore, interfacial temperature in the welded joint during welding with optimised electrodes (about 915 °C) was lower than that with F type electrodes (about 985 °C).

1. Introduction

Imposed by the urgent situation of energy scarcity and environmental pollution, automobile lightening which could reduce fuel consumption and exhaust emissions has attracted increased interests. The use of lightweight materials such as aluminium alloy in automobile manufacturing provides an effective means to achieve automobile lightening [1,2]. Attributing to its inherent problems in terms of cost and security performance, the design and manufacturing of an all-aluminium vehicle body structure which could obtain a weight reduction of nearly 50% compared with traditional steel vehicle body structure have not yet been extensively adopted in automotive industry [3]. Nevertheless, the employment of hybrid vehicle body structure composed of both aluminium alloy and high strength steel parts turns out to be a compromise between cost and security performance [4]. The hybrid vehicle body structure signifies welding and joining of dissimilar materials of aluminium alloy and high strength steel. It is difficult to obtain a reliable welded joint of aluminium alloy and steel by traditional fusion welding due to their discrepancies in thermophysical properties, which readily favouring the formation of welding defects such as cracks, porosities and cavities [5–7]. Furthermore, the formation of brittle Al-rich intermetallic compounds involving $FeAl_3$ [5,6], Fe_2Al_5 [5–7] and $FeAl_2$ [5,7] facilitated by the nearly zero solid solubility of iron in aluminium would degrade mechanical properties of the welded joint. Mechanical joining techniques such as clinching, screwing, self-piercing riveting (SPR) and adhesive bonding are used to join dissimilar materials of aluminium alloy and steel in automotive industry to date. SPR could be regarded as an effective means to join aluminium alloy and steel parts [8,9], whereas the inherent problems in regard to joint appearance, potential weight increase, access constraint and ease of rupture have restricted its application [10].

Several solid state welding methods such as explosive welding [11,12], ultrasonic welding [13], magnetic pulse welding [14], friction welding [15] and friction stir welding [16–18] are adopted to weld aluminium alloy and steel. The brittle intermetallic compounds are desired to be diminished by using these solid state welding methods. Intermetallic compounds composed of AlFe, Al_2Fe, Al_3Fe and Al_6Fe were formed in the explosive welded joint of aluminium alloy and steel, meanwhile thickness of the intermetallic compound layer could be reduced with the employment of stainless steel or aluminium interlayer due to the decrease in collision energy [12]. Prangnell et al. suggested that the intermetallic compounds (Fe_2Al_5 and $FeAl_3$) formed in the ultrasonic welded joint of A6111 aluminium alloy and DC04 steel would reduce mechanical properties of the welded joint if their thickness exceeded 1 μm [13]. Lee et al. found that an intermediate layer composed of fine Al grains, fine fragments of SPCC and dispersive intermetallic particles

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

Elements, wt.%	C	Si	Cu	Fe	Mg	Mn	Zn	Ti	V	S	P	Nb	Al
6008-T66	…	0.56	0.15	0.19	0.45	0.07	0.007	0.02	0.08	…	…	…	Balance
H220YD	0.007	0.09	…	Balance	…	0.51	…	0.01	…	0.007	0.05	0.02	…

(Fe_2Al_5 and $FeAl_3$) was formed in the magnetic pressure seam welded joint of SPCC steel and A6111 aluminium alloy [14]. Intermetallic compounds composed of Fe_2Al_5 and FeAl with overall thickness of 350 nm were formed in the friction welded joint of 6061-T6 aluminium alloy and AISI 1018 steel [15]. Watanabe et al. revealed that interfacial intermetallic compounds involving FeAl and $FeAl_3$ were formed in the upper friction stir welded joint of 5083 aluminium alloy and mild steel, and that tensile strength of the welded joint reached 86% that of the base metal of aluminium alloy. Besides, cracks inclined to propagate through the intermetallic compounds [16,17]. The adaptability of these solid state welding methods is restrained to a certain extent in automotive industry due to the limitation on configuration and capacity of welding equipments. Besides, arc welding–brazing [19,20] and laser brazing [21–23] are also employed to weld aluminium alloy and steel. The results indicated that composition, morphology and thickness of the intermetallic compounds could be regulated with the introduction of filler metals, whereas cracks also tended to initiate at the intermetallic compounds and then propagate through them.

Few studies corresponding resistance spot welding of aluminium alloy and steel have been reported to date, although it is a major welding method in automobile manufacturing [24,25]. Some additional materials such as aluminium interlayer [26], cover plate [27] and cold rolled aluminium clad steel strip [28,29] were used during resistance spot welding of aluminium alloy and steel. Hwang et al. illustrated that the introduction of aluminium interlayer could reduce thickness of the intermetallic compound layer in the welded joint of A5086 aluminium alloy and SS400 steel [26]. Qiu et al. suggested that an increase in nugget diameter of the welded joint was achieved due to the employment of cover plate located between electrode and aluminium alloy [27]. Sun et al. revealed that an intermetallic compound layer with thickness of 8.5 μm was formed in the welded joint of AA5182 aluminium alloy and SAE1008 steel with the employment of aluminium clad steel strip, and that a hybrid fracture mode was obtained for the welded joint [28]. A tensile shear load up to 3.5 kN was obtained for the welded joint of Al–Mg alloy and steel with the employment of aluminium clad steel interlayer [29]. Nevertheless, the introduction of additional materials brings in weight increase, which deviates from the requirement by automobile lightening.

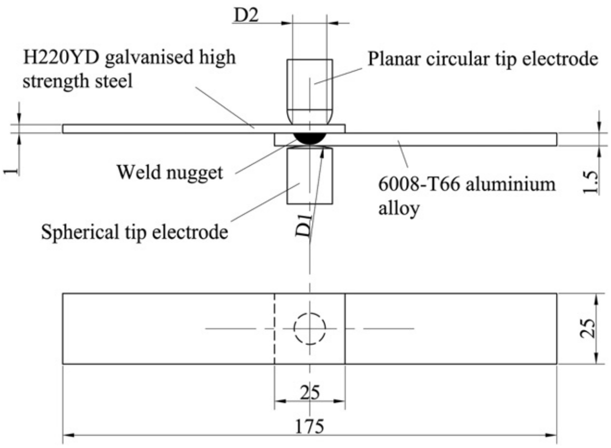

Fig. 1. Schematic diagram of resistance spot welding arrangement (not to scale, dimensions in mm).

In the study, a novel resistance spot welding method of dissimilar materials of aluminium alloy and galvanised high strength steel is presented. The morphology of welding electrodes is designed optimally, and the effect of electrode morphology on weldability of the dissimilar materials is studied. The welding current density distribution and temperature field of the welded joints during welding with optimised electrodes and traditional F type electrodes are both revealed. Macrostructure, microstructure and tensile shear load of the welded joints obtained with optimised electrodes are studied as well.

2. Experimental procedure

The dissimilar materials used were 6008-T66 aluminium alloy sheets with thickness of 1.5 mm and H220YD galvanised high strength steel sheets with thickness of 1.0 mm. Chemical compositions of the dissimilar materials are shown in Table 1. The steel sheets were galvanised by means of hot dipping, and the thickness of the zinc layer coating was 7 μm on both surfaces. Both aluminium alloy and steel specimens were machined into a size of 100 mm × 25 mm. Prior to welding, the aluminium alloy specimens were grinded by using abrasive paper (grade 800) and degreased in acetone in sequence. Meanwhile the steel specimens were just degreased in acetone. Lap joint configuration was employed during resistance spot welding. The cap-type electrodes made of CuCrZr alloy were used, and the morphology of the electrodes was designed optimally to solve the inherent problems [24,30] in resistance spot welding of aluminium alloy and galvanised high strength steel and improve weldability of the dissimilar materials. A spherical tip electrode on aluminium alloy side and a planar circular tip electrode on galvanised high strength steel side were employed during welding. Specifically, spherical diameter ($D1$) of the spherical tip electrode on aluminium alloy side used was 30 mm, 50 mm, 70 mm and 100 mm, respectively. In the meantime, tip diameter ($D2$) of the planar circular tip electrode on steel side used was 8 mm, 10 mm, 12 mm and 14 mm, respectively. Fig. 1 shows the schematic diagram of the resistance spot welding arrangement. Welding experiments were carried out by using a median frequency direct current (MFDC) resistance spot welding machine quipped with Rexroth PSI 6300 controller and Nimak LHN4 welding gun. MFDC resistance spot welding was superior to industrial frequency alternative current resistance spot welding in dissimilar material welding of aluminium alloy and galvanised high strength steel as the former welding method could supply more stable current and higher power efficiency than the latter one. The welding parameters used were shown as follows: welding current (19 kA–25 kA), welding time (250 ms–350 ms), electrode force (3 kN–3.5 kN), squeezing time (400 ms) and

Table 2
Optimised resistance spot welding parameters used under different tip diameters of planar circular tip electrode on steel side with spherical diameter of spherical tip electrode on aluminium alloy side being fixed as 70 mm.

Tip diameter (mm)	Welding current (kA)	Welding time (ms)	Electrode force (kN)	Squeezing time (ms)	Keeping time (ms)
8	21	250	3	400	400
10	22	300	3.5	400	400
12	24	350	3.5	400	400
14	25	350	3.5	400	400