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Characterization of intermetallics in aluminum to zinc coated interstitial free steel joining by pulsed MIG brazing for automotive application

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ABSTRACT

In order to meet the demand for lighter and more fuel efficient vehicles, a significant attempt is currently being focused toward the substitution of aluminum for steel in the car body structure. It generates vital challenge with respect to the methods of joining to be used for fabrication. However, the conventional fusion joining has its own difficulty owing to formation of the brittle intermetallic phases. In this present study AA6061-T6 of 2 mm and HIF-GA steel sheet of 1 mm thick are metal inert gas (MIG) brazed with 0.8 mm Al–5Si filler wire under three different heat inputs. The effect of the heat inputs on bead geometry, microstructure and joint properties of MIG brazed Al-steel joints were exclusively studied and characterized by X-ray diffraction, field emission scanning electron microscopy (FESEM), electron probe micro analyzer (EPMA) and high resolution transmission electron microscopy (HRTEM) assisted X-ray spectroscopy (EDS) and selective area diffraction pattern. Finally microstructures were correlated with the performance of the joint. Diffusion induced intermetallic thickness measured by FESEM image and concentration profile agreed well with the numerically calculated one. HRTEM assisted EDS study was used to identify the large size $FeAl_3$ and small size Fe_2Al_5 type intermetallic compounds at the interface. The growth of these two phases in A2 (heat input: 182 J mm^{-1}) is attributed to the slower cooling rate with higher diffusion time (~61 s) along the interface in comparison to the same for A1 (heat input: 155 J mm^{-1}) with faster cooling rate and shorter diffusion time (~24 s). The joint efficiency as high as 65% of steel base metal is achieved for A2 which is the optimized parameter in the present study.

1. Introduction

Now-a-days, a wide variety of materials such as aluminum, magnesium and plastics are being extensively used in modern vehicles, though steel remains the prime material in automobile industry. But with increasing demand for light weight, fuel economic and less fume emissive vehicles, not only high strength and ultra-high strength steels are currently being a subject of interest, but also significant efforts being made toward establishing multi-material fabrication process. Substitution of steel by aluminum in the car body structure is an emerging area of interest for both research and industry. However, sound joints between dissimilar materials with low cost fabrication process require to be established. But the availability of sound joining technique for dissimilar material is indispensible. Joining of aluminum to steel by conventional fusion welding methods is difficult due to the large differences in thermo-physical properties (such as melting point, thermal conductivity and thermal expansion) which lead to high distortion, residual stresses etc. Also the metallurgical characteristics result in formation of brittle intermetallic phases which degrade the joint quality. Formation of the intermetallic phases is mainly driven by the diffusion of the elements at the interface and is highly dependent on the cooling time and temperature history of the joining process [1–7]. Further, other solid state joining processes like diffusion bonding, friction welding, friction stir welding and explosive welding are also applicable for joining of aluminum to steel [8–12]. But these processes are difficult to apply for joining complex shaped components and different positional welding.

The metal inert gas brazing (MIGB), is similar to MIG welding except the filler wires normally used non-ferrous alloys such as $AlSi_5$, $AlSi_{12}$ etc. whose melting point is lower than the base metal (steel) and with good wettability properties [5,13]. This process has the advantage of both gas metal arc welding (GMAW) and conventional brazing. During MIG brazing for joining such dissimilar material combination, the molten pool formed by the melting of low melting filler material (aluminum) wets the base materials to form a joint. Wetting is governed by temperature and viscosity of the filler metal, temperature difference between the molten pool to substrate and surface tension.

Several research studies have been reported on joining coated steel to aluminum sheet using both solid state and fusion welding processes such as friction stir welding, cold metal transfer, laser welding, gas

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Table 1
Chemical composition and mechanical property of base metals.

Base metal	Thickness (mm)	Chemical composition (Wt%)						Mechanical properties		
		C	Mn	Al	Si	Mg	Fe	YS (MPa)	UTS (MPa)	Braking load (kN)
HIF steel	1.00	0.0024	0.47	0.042	0.094	–	Bal.	225	375	7.50
Aluminum	2.00	–	0.15	Bal.	0.52	0.91	0.60	172	295	11.80

tungsten arc welding etc. [14–20]. But limited publications are available on joining of coated steel to aluminum sheet using MIG/Arc brazing. Murakami et al. [5] reported that only 80 MPa tensile strength was achieved using flux cored $AlSi_{12}$ filler wire but there is paucity information about the microstructure study. Zhang et al. [21] joined aluminum alloy (2B50) to aluminized and galvanized coated stainless steel (1Cr18Ni9Ti) with $AlSi_5$ filler wire and observed that aluminized coating had limited effect to promote weld surface appearance. Also the tensile strength of aluminized coating is lower compare to galvanized coating. Su et al. [22] remarked that Fe_2Al_5, $FeAl_3$ and Fe_3Al types of intermetallic compounds was formed during welding of 5052 aluminum alloy to galvanized mild steel sheets in lap joint configuration using $AlSi_{12}$ filler wire. Tensile strength of 201 MPa and 115 MPa was achieved by AC double-pulse gas metal arc welding (ADG) and DC pulse gas metal arc welding (DPG) respectively. Su et al. [23] also studied about the influence of different filler wires (pure Al, $AlSi_5$, $AlSi_{12}$ and $AlMg_{4.5}$) on microstructure and mechanical property. Thicker interface produced by Al–Mg filler wire attributed weaker joint strength compare to Al–Si filler wire. Furthermore, evaporated zinc from galvanized steel entrapped into the weld pool resulting in large amount of porosity which was relatively higher in AC process than DC process [24]. Kobayashi et al. [25] reported the presence of Fe_2Al_5 phases in the coating layers of hot dip aluminized steel and subsequent diffusion-treatment process produced FeAl and Fe_3Al phases at temperature greater than 1273 K. From the law of Arrhenius, it can be predicted that the thickness of intermetallic compound such as Fe_2Al_5 phase is affected by both temperature and time. In order to improve mechanical property the formation of brittle Fe_2Al_5 and $FeAl_3$ in Fe–Al joint should be decreased by reducing the heat input. Sasaki et al. reported that, the Fe_2Al_5 compound is formed first by the reaction of aluminum as it diffuses into the steel substrate and then other Fe–Al intermetallic compounds are produced during the subsequent heating process. The growth of Fe_2Al_5 phase is governed by volume diffusion [26–28]. From the above discussion, it is clear that the formation of intermetallics cannot be avoided by MIGB process using low melting filler wire. But detailed study of microstructures, formation and role of intermetallics on mechanical property (i.e. hardness and strength) of the MIG brazed joint are still scarce in literature.

In the present investigation an attempt has been made to join aluminum alloy (AA6061-T6) to zinc coated (galvannealed) interstitial free (IF) steel sheet using solid Al–5Si filler wire by pulse MIG brazing. The main focus of the present work is to characterize the microstructure of brazed joints by optical microscopy, field emission scanning electron microscopy (FESEM), X-ray diffraction (XRD) and high resolution transmission electron microscopy (HRTEM) to understand the formation, size distribution of intermetallics and whether the diffusion is also worth considering or not. Further, efforts have been made to correlate the microstructure with the performance of the joints.

2. Experimental procedure

Aluminum alloy (AA6061-T6) of 2 mm thickness and high strength grade galvannealed IF (HIF-GA) steel sheet of 1 mm thickness are MIG brazed with 0.8 mm diameter solid Al–5Si filler wire using 100% argon as shielding gas at a flow rate of 12 l min^{-1}. The chemical composition and mechanical property of base metals are shown in Table 1. At first, the as-received sheets were degreased by acetone and suitably clamped in lap joint configuration before MIGB. MIGB of the lap joint was performed using a pulsed-synergic machine (TransPuls Synergic 2700, Fronius) attached with a semi-automatic side beam carriage. Brazing was carried out under synergic pulse mode at different heat inputs with varying current as given in Table 2. The heat input for each welding parameter was calculated using $(\eta UI \times 60)/v$, where U is mean welding voltage (V), I is mean welding current (A), v is the traverse speed (mm min^{-1}) and η is process coefficient ($\eta_{MIGB} = 0.7$) [29].

During the experiment single side lap joints with 20 mm overlap, 70° travel angle and 20° working angle was maintained (Fig. 1). The torch was traversed automatically along with 2 mm offset toward aluminum side which was at the edge of the upper sheet and this process is carried out with push mode (as shown in Fig. 1c). Temperature profile of the joint region near the interface for the three different heat inputs were measured with a K-type (Chrome–Alomel) thermocouple of 1.5 mm diameter using a digital temperature recorder (MV1000, Yokogawa). After MIG brazing, the samples were cut from the joint region across the transverse section of the brazed sheet for metallographic, micro-hardness and shear tensile testing. Metallographic specimens were polished with successive grades of emery papers up to 1000 grit size followed by cloth polishing with 1 μm diamond paste. The metallographic specimens were examined under optical microscope (OM; Axio Imager A1m, Carl zeiss) and field emission scanning electron microscope (FESEM; SUPRA25, Zeiss) equipped with energy dispersive X-ray spectroscopy (EDS; Oxford, liquid N_2 cooled) and electron probe micro analyzer (EPMA; JXA-8230, JEOL). Metallographic specimens were again cut using diamond cutter and polished down to a thickness less than 100 μm. The interface area then further polished down to 20 μm using ion-miller and a 3 mm disk near the interface area was punched out from the bulk specimen for high resolution transmission electron microscope (HRTEM; CM12, Philips) analysis. X-ray diffraction (XRD; X' Pert Pro, PANalytical Instruments) analysis were carried out using target of Cu kα to identify the phases (intermetallic compound) formed at the Al-steel joints. Micro-hardness measurements were taken at a load of 25 gf using a standard Vicker's micro-hardness testing machine (AMH43, LECO). Finally, the lap joint samples were machined to prepare standard shear tensile test specimens following DIN EN10002-1 standard (Gauge length: 120 mm and width: 20 mm) [30]. Tensile shear tests were carried out in a 100 kN capacity

Table 2
MIG brazing parameters with Al–5Si filler wire.

Sample No.	Mean current (A)	Mean voltage (V)	Pulse frequency (Hz)	Welding speed (mm min^{-1})	Heat input (J mm^{-1})	Peak temp. (K)	Avg. interface thickness (μm)
A1	70	18.5	60	350	155	985	6.1
A2	80	19.0	60	350	182	1118	10.1
A3	100	19.6	60	350	235	1301	13.7