Journal of Manufacturing Processes 31 (2018) 494–501

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Welding of Al-Mg aluminum alloy to aluminum clad steel sheet using pulsed gas tungsten arc process

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ARTICLE INFO

Article history:
Received 22 September 2017
Received in revised form
22 November 2017
Accepted 7 December 2017

Keywords:
Aluminum clad steel
Pulsed gas tungsten arc welding
Heat-input
Intermetallic compound
Stress analysis
Strength

ABSTRACT

Al-Mg aluminum alloy was lap joined to aluminum clad steel sheet using *pulsed gas tungsten arc welding* process and Al-Si filler metal. The effects of the welding heat-input were investigated on the joint microstructure and mechanical properties. Weld metal microstructure, formation of intermetallic compounds (IMCs) at the joint interface and the fracture locations were studied using stereo, optical and scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS). The joint strength of the welds was evaluated by shear-tensile test. The results showed that presence of a thin aluminum clad layer with 350 μm thickness drastically decreased the Al-Fe intermetallic thickness at the weld seam/steel interface to less than 2.5 μm. The joint strength increased with enhancement of the heat-input up to an optimum value and then decreased beyond it. This behaviour was justified in the light of the contradictory effects of the weld metal microstructure and adhesion of the weld metal to the aluminum clad layer near the weld root. In the optimum heat-input of 250 J mm^{-1}, the joint strength reached to ~90% of Al-Mg aluminum base metal strength. In all the welds, fracture path had an angle of 75 ± 3° with respect to the horizontal base plane. Stress analysis in the weld showed that fracture in the joint was controlled predominantly by the maximum normal stress rather than the maximum shear or *von Mises* effective stress.

1. Introduction

Steel/aluminum hybrid parts are increasingly used in various industries such as automotive, aerospace and shipbuilding due to suitable mechanical strength and low cost of steels as well as low density and high corrosion resistance of aluminum alloys, resulting in reduction of the structure weight and fuel consumption [1–6]. Therefore, joining of aluminum alloys to steels is an essential need in transportation industries. However, joining of steels to aluminum alloys by conventional fusion welding processes is difficult due to the large difference between the melting points and thermal conductivity coefficients of steel and aluminum alloys and also formation of thick and brittle Al/Fe intermetallics (IMCs) at the joint interface [2,4,7–11]. From this point of view, solid-state welding processes may be more appropriate for joining of steels to aluminum alloys since base metals do no melt during welding and thinner IMCs are formed in comparison to the fusion welding processes [12–15]. On the other hand, fusion welding techniques are generally more economical and flexible compared to the solid-state processes. Solid-state processes suffer from limitations in shape and size of the components, need for especial tools and relatively expensive equipments [10,15,16].

Some modified fusion welding processes were used in order to reduce Al/Fe intermetallic layer thickness by controlling the heat-input. Madhavan et al. [17] investigated the conventional and pulsed cold metal transfer (CMT) welding of aluminum to dual phase (DP) steel. They found out that Al/Fe intermetallic layer thickness at the joint interface decreased significantly especially in the pulsed CMT (intermetallic layer thickness less than 1.5 μm). Das et al. [18] joined AA5754 aluminum alloy to galvanized steel sheet using a short-circuiting metal transfer gas metal arc process with a low heat-input and reported that Al/Fe intermetallic layer with the thickness of 0.68–6.10 μm was formed along the joint interface. Furthermore, Shi et al. [19,20] used pulsed double-electrode gas metal arc welding (DE-GMAW) for joining of aluminum to galvanized steel sheets. DE-GMAW is a newly developed process that can decrease the welding heat-input and increase the energy needed to melt a given amount of the filler metal. Their results showed that IMCs at the joint interface mainly consisted of Al_5Fe_2 or $Al_5Fe_2Zn_X$ at the steel side and Al_3Fe at the aluminum side. The maximum shear-tensile strength of the joints was around ~187 MPa, about 89% of the aluminum base metal strength.

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https://doi.org/10.1016/j.jmapro.2017.12.008
1526-6125/

Table 1
Chemical composition (wt.%) and mechanical properties of the base materials.

Material	Chemical compositions (wt-%)						UTS (MPa)	Elongation (%)
	Al	Fe	C	Mn	Si	Mg		
Al-5052-H34	Bal.	0.23	–	0.005	0.06	2.36	245	12
Al-1050-O	Bal.	0.40	–	0.05	0.25	0.05	80	34
St-12-O	–	Bal.	<0.10	0.50	0.04	–	280	45
4047 Al-Si	Bal.	0.18	–	0.01	11.5	–	127	12

Use of an inter-layer such as zinc, between aluminum and steel sheets, has been investigated in order to decrease the problem of IMCs formation in both fusion [7,8] and solid-state [14,21] processes. Ratanathavorn and Melander [14] explored the role of zinc layer on the intermetallic formation and joint properties in friction stir lap welding of AA5754 aluminum alloy to galvanised ultra-high strength steel. They reported that Al_5Fe_2 and $Al_{13}Fe_4$ phases were formed at the joint interface in both galvanized and uncoated steel base metal. The best joint strengths were obtained for the thicker galvanised layer, however; at high tool transverse speed, excessive galvanised zinc remained on the interface which degraded the joint quality. Furthermore, their results showed that some porosity was formed in the joint due to the presence of partial liquid phase in the aluminum matrix. Arghavani et al. [7] studied the effects of the zinc layer in the resistance spot welding of 5052 aluminum alloy to low carbon galvanized steel. They showed that Al/Fe intermetallic layer thickness decreased due to the consumption of the welding heat-input by melting and evaporation of the zinc layer. Wan et al. [22] investigated the IMCs at the interface of Al 6022-T4/galvanized mild steel resistance spot welds. They reported that the intermetallic layer included Al_5Fe_2 and Al_3Fe phases with the thickness of less than 1 μm and 2–9 μm, respectively. Also, Su et al. [23] investigated 5052 aluminum alloy/galvanized mild steel lap joint made by gas metal arc welding. They reported that zinc layer can improve the wetting of the molten aluminum alloy and filler metal on the steel surface. However, zinc may vaporize and enter into the welding pool resulting in the formation of pores in the weld. Instead of zinc layer, aluminum alloys can be used as an inter-layer between aluminum and steel sheets. Aluminum clad steel sheets (with a commercially pure aluminum layer coated on the steel sheet) are widely produced in the world. Higher melting point of aluminum compared to zinc results in higher working temperature of the joints made by the aluminum clad steel sheets than that of the joints made by galvanised steels. On the other hand, aluminum has higher evaporation point and lower vapour pressure in comparison to zinc. Consequently, possibility of the porosity formation at the joint area decreases in the fusion welding of the aluminum clad steel sheets. Movahedi et al. [15] studied the friction stir lap welding of Al-5083 aluminum alloy to the aluminum clad steel sheet and obtained a sound and defect free joint between the Al-5083 sheet and aluminum clad layer. They also did not observed Al/Fe IMC at the interface of the steel base metal and the aluminum clad layer.

The objective of the present study is lap joining of Al-Mg aluminum alloy sheet to aluminum clad steel sheet using *pulsed gas tungsten arc welding* (GTAW) that has not been investigated so far, according to the best knowledge of the authors. Al-Si filler metal is used for welding. Effects of heat-input on the formation of intermetallic reaction layer, microstructure of the weld seam and shear strength of the joints are explored. Stress analysis in weld is also used in order to justify the fracture location in the welds.

2. Experimental procedure

Al-5052-H34 aluminum alloy sheet (with thickness of 3 mm) and Al-1050 clad St-12 steel sheet (with St-12 thickness of 1 mm and Al-1050 thickness of 350 μm) were used as the primary materials. The chemical composition and mechanical properties of the materials are given in Table 1. Aluminum clad steel sheets were produced in two stages. First, the bi-layer sheets were prepared using roll bonding process with 0.50 reduction in thickness as mentioned in reference [24]. Then, the roll bonded samples were heat treated at 450 °C for 90 min [24]. The strength of the roll bonded sheets after heat treatment was evaluated by peel test according to the ASTM-D1876-08 standard. The peel strength of the joints reached to the strength of Al-1050 base sheet and thus, fracture occurred from Al-1050 clad layer during the peel test.

Table 2
Range of parameters used for pulsed GTAW.

Parameter	Unite	Value
Base current	Amps	40
Peak current	Amps	95–145
Welding speed	$mm.min^{-1}$	100–120
Pulse duration	%	50
Pulse frequency	Hz	100
Arc length	mm	4–6

The Al-5052 sheets were lap joined to Al-1050 clad St-12 sheets by pulsed GTAW process with five levels of heat-input, i.e. $\sim 100 J.mm^{-1}$, $\sim 150 J.mm^{-1}$, $\sim 250 J.mm^{-1}$, $\sim 340 J.mm^{-1}$, and $\sim 380 J.mm^{-1}$. The welding parameters were chosen using primary experiments as well as the literature [25,26] and their values are listed in Table 2. The base current, pulse duration and pulse frequency were constant for all the welds. The welding heat-input was changed with variation of peak current and welding speed. In the pulsed GTAW, weld penetration, fusion of the base metals and filler metals and the microstructure of the weld metal are affected by the peak current. However, some of the weld pool heat is lost during the base current. Indeed, current pulsation leads to the adequate penetration of the weld with the lower welding heat-input. Moreover, high pulse frequency refines the microstructure of the weld metal. 4047 Al-Si rod with 2 mm diameter was used as the filler metal. The shielding gas was argon with a flow rate of $8 L.min^{-1}$. Also, the manual feeding rate of the filler metal was changed from $\sim 200 mm.min^{-1}$ to $\sim 250 mm.min^{-1}$ (due to the small variation of the welding speed) in order to deposit a relatively constant amount of the filler metal in the various specimens with different welding speeds. Alternating current was used during welding. The Al-5052 sheet was placed on top of the Al-1050 clad St-12 sheet with 20 mm wide overlap, as illustrated schematically in Fig. 1. The schematic diagram of GTAW process and oscillogram of electrical current are given in Fig. 2.

Stereo and optical microscopes as well as field-emission scanning electron microscope (FESEM) equipped with energy dis-

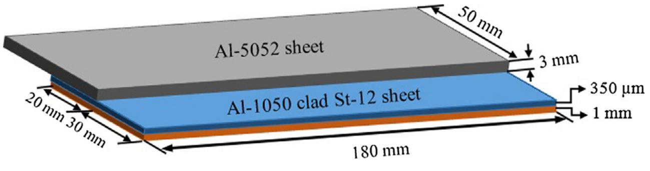

Fig. 1. Lap joint configuration and dimensions of the samples.