Journal of Materials Processing Technology 214 (2014) 750–755

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Influence of alloy elements on microstructure and mechanical property of aluminum–steel lap joint made by gas metal arc welding

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ARTICLE INFO

Article history:
Received 3 September 2013
Received in revised form
20 November 2013
Accepted 21 November 2013
Available online 1 December 2013

Keywords:
Dissimilar metal joining
Al–Si alloy
Al–Mg alloy
Galvanized steels
Intermetallic compounds

ABSTRACT

5052 aluminum alloy sheets and galvanized mild steel sheets were joined in lap configuration by alternate-current double pulse gas metal arc welding with pure Al, Al–5Si, Al–12Si and Al–4.5Mg (wt%) filler wires. The effect of alloying elements on the microstructure of intermetallic compounds (IMC) layers formed between weld seam and steel, and tensile strength of the resultant joints were investigated. The thickness of IMC layer in all samples varied along the cross-section of the joint, the intermediate part of the IMC layer was thicker than the head and root parts. The diffusion of Si into Fe_2Al_5 sub-layer could restrain the growth of Fe_2Al_5 sub-layer and IMC layer, and joint's mechanical property improved with the increasing Si content in Fe_2Al_5 phase. Due to the high hot crack sensitivity of Al–4.5Mg alloy, cracks generated at the root of joint made with Al–4.5Mg filler, resulting in poor mechanical property.

1. Introduction

In case of Fe–Al dissimilar materials welding–brazing, the great difference in physical and chemical properties between steel and aluminum alloys made joining Al to steel become very challenging, as reported by Liu et al. (2006). Song et al. (2009a) revealed that brittle Fe–Al intermetallic compounds (IMC) layer was easily formed at the interface between seam and steel sheet due to the extremely low solid solubility of iron in aluminum. Kobayashi and Yakou (2002) pointed out that this IMC layer, mainly composed of brittle Fe_2Al_5 and $FeAl_3$ phases, was a critical factor detrimental to mechanical property of the joint. That was because cracks were inclined to originate from this IMC layer, when joint was under tensile strength. Bouayad et al. (2003) remarked that the growth of this IMC layer was governed by temperature and time. Naoi and Kajihara (2007) illustrated that the thickness of the Fe_2Al_5 layer l could be expressed as a function of annealing time t by parabolic relationship: $l = K_0 \exp^{(-Q/RT)} t^{-1/2}$, in which K_0 was the parabolic coefficient, T was temperature and Q was activation energy. Reducing linear heat input in welding process is an effective method to reduce molten pool temperature, decrease the thickness of IMC layer and improve the mechanical property of the joint. Linear heat input can be expressed as $Q = UI/v$, in which U is mean welding voltage, I is mean welding current and v is welding speed. Besides heat input reduction, alloy elements, which can be added into the weld seam through filler wires in welding process, affect the thickness and micro-hardness of the IMC layer as well. Lin et al. (2010) conducted tungsten inert gas butt welding–brazing between 5A06 aluminum alloy and SUS321stainless steel with Al–6Cu (wt%, all of the following elements compositions are weight ratios) filler wire. The 3–5 μm thick IMC layer, which was mainly composed of $FeAl_3$, had an average micro-hardness of 644.7 HV, and the tensile strength of butt joint reached 172.5 MPa. Song et al. (2009b) joined 5A06 aluminum alloy to AISI 321 stainless steel by TIG welding–brazing with pure Al, Al–5Si and Al–12Si filler wires, and pointed that Si additions had the greatest effect in preventing the build-up of the IMC layer, and minimizing its thickness. Dong et al. (2012) joined aluminum alloy sheets to galvanized steel sheets by gas tungsten arc welding with Al–5Si, Al–12Si, Al–6Cu, Al–10Si–4Cu and Zn–15Al filler wires. It was found that the thickness of the IMC layer decreased and tensile strength of the joint increased with the increase of Si content in the weld. Shih and Tu (2007) investigated the reactive iron–aluminum intermetallic layer, which grew at the interface between the melt and the steel substrate, and found that the reactive layer of a 1040 steel bar dipped in an Al–7Si–0.4Mg melt for a given dipping time at 973 K, had the minimum thickness among all melts, including pure Al, Al–7Si, Al–1Mg and Al–7Si–0.4Mg alloys. The diffusion of Si into the reactive layer could greatly reduce the Al and carbon diffusion capability and the Al–Fe reaction rate; Mg could gradually

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0924-0136/$ – see front matter
http://dx.doi.org/10.1016/j.jmatprotec.2013.11.022

Table 1
Chemical compositions of 5052 Al alloy and galvanized mild steel sheets (wt%).

Al	Si0.25	Fe0.40	Cu0.10	Mn0.10	Mg2.50	Cr0.15	Zn0.10	Ti0.15	Al balance
Steel	C0.050	Si0.020	Mn0.60	P0.0090	Si0.019	Fe balance			

build up at the interface between the reactive layer and the melt, leading to the formation of a binary Mg–Al intermetallic phase to block the diffusion of Al element into the reactive layer. According to the researches mentioned above, it can be concluded that Si and Mg may have the possibility of inhibiting the growth of IMC layer formed between steel and molten Al. Moreover, the Al–Si and Al–Mg wires are commonly used in welding Al alloys to improve the fluidity or the mechanical properties of the weld seam.

Alternate-current double pulse gas metal arc welding can effectively reduce the linear heat input in welding process due to cyclic polarity changing and the addition of a low frequency current pulse. It has been reported by Kumar et al. (2009) that this welding method offered many advantages such as high wire melting efficiency, low heat input and controlled weld penetration. Su et al. (2013) remarked alternate current double pulse gas metal arc welding was a more feasible method to make robust Fe–Al lap joints. In this paper, alternate-current double pulse gas metal arc welding was conducted to join Al alloy to steel with pure Al, Al–5Si, Al–12Si and Al–4.5Mg filler wires. The effect of alloy elements on thickness, morphology and composition of IMC layer in joints made with this innovative method was investigated.

2. Experimental methods

According to Non-Ferrous Industry Standard of P.R. China, the thickness of Al alloys used in automobile body manufacturing should range from 0.7 to 2.5 mm, so 1 mm thick 5052 aluminum alloy and 1 mm thick galvanized mild steel sheets for automobile application with dimensions of 300 mm × 50 mm were used in this study, and their chemical compositions are listed in Table 1. The zinc coating in galvanized mild steel can help to enhance the wetting of the molten aluminum alloy and filler metal onto the steel surface in welding process, as revealed by Zhang and Liu (2011). Filler metals adapted were pure Al (ER1100), Al–5Si (ER4043), Al–12Si (ER4047) and Al–4.5Mg (ER5356), with diameter of 1.2 mm. Shielding gas used in this experiment was pure argon (99.9%), and the gas flow was 12 L/min. The Al alloy sheet was placed on top of the steel sheet with 10 mm wide overlap, as shown in Fig. 1. With respect to the 20° angle of nozzle, the aim was to avoid insufficient molten of Al alloy sheet and the appearance of cracks in the weld root. Further increase of the nozzle angle would restrain the generation of seam–steel interface. The welding locations of base metals were cleared with acetone before welding. Welding parameters listed in Table 2 are optimum values, making sure the molten pool temperature was around 690 °C, based on our previous experiments. Metallographic specimens of weld cross-sections were cut out from the resulted joints and polished. The metallographic specimens were observed through Zeiss AxioCam MRc5 optical microscope and Zeiss ULTRA 55 scanning electron microscope. Lap shear tensile test samples being 100 mm long and 12 mm wide were also cut out from the resulted Fe–Al joints. The specimens were pulled by Zwick Roell Z020 testing machine with a constant loading rate of 1 mm/min.

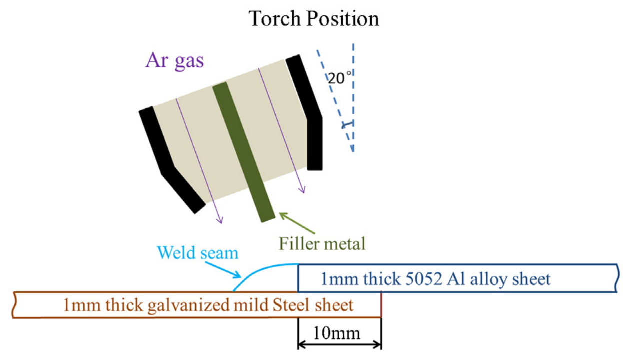

Fig. 1. Schematic diagram of the gas metal arc welding process.

3. Results and discussion

3.1. Effect of pure Al and Al–4.5Mg filler wires on the microstructure of IMC layer

In joints made with pure Al and Al–4.5Mg filler wires, the thickness and morphology of IMC layers vary along the cross-section of joints, as revealed in Fig. 2a. Similar phenomenon was reported by Mathieu et al. (2007), who divided the IMC layer into three different zones according to thickness difference along the IMC layer: the head, the intermediate part and the root, as shown in Fig. 3a. In joints made with pure Al and Al–4.5Mg filler wires, the root of IMC layer (about 6–7 mm in length) has wedge shaped morphology and its thickness ranges from 2 μm to 7 μm, as revealed in Fig. 2b and d. In contrast, the intermediate part of IMC layer (about 1–2 mm in length) with lath shaped morphology is about 30 μm thick, as shown in Fig. 2c and e. Lin et al. (2009) revealed that seam–steel interface was made up of two kinds of intermetallic layers. Song et al. (2009a) also found joint interface consisted of the θ-$FeAl_3$ in aluminum side and η-Fe_2Al_5 in steel side. In present experiment, similar phenomenon can be observed at the root part of IMC layer as well, as shown in Fig. 2b. The dotted line, defined by image contrast, reveals the interface between these two phases. Because of the micro-hardness difference between $FeAl_3$ (700 HV) and Fe_2Al_5 (1100 HV), terrace will generate at $FeAl_3$ and Fe_2Al_5 interface after polishing process, hence resulting in contrast in SEM observation. Energy dispersive spectrometry (EDS) analysis was also conducted to analyze the compositions of sub-layers. About 5–8 points in each sub-layer were selected and typical results are listed in Table 3. The EDS results verify these two sub-layers correspond to $FeAl_3$ and Fe_2Al_5 phases respectively, as marked in Fig. 2b. In the

Table 2
Welding parameters.

Filler wire	Parameters				
	Wire feed speed (m/min)	Welding speed (m/min)	Average voltage (V)	Average current (A)	Frequency of superimposed current pulse (Hz)
Pure Al	3.3	0.5	16.2	55	15
Al–5Mg	4.3	0.5	16.0	55	15
Al–5Si	3.3	0.5	16.2	56	15
Al–12Si	3.3	0.5	16.2	55	15