Effects of Gap Width and Groove on the Mechanical Properties of Butt Joint Between Aluminum Alloy and Stainless Steel

Honggang DONG^{1)†} and Chuanqing LIAO^{1,2)}

1) School of Materials Science and Engineering, Dalian University of Technology, Dalian 116085, China

2) Shanghai Aerospace Equipments manufacturer, Shanghai 200245, China

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Butt joining of 5A02 aluminum alloy to 304 stainless steel sheets was conducted using gas tungsten arc welding process with Al-12%Si (wt.%, the same below) and Zn-15%Al flux-cored filler wires. The effects of gap width and groove in steel side on the microstructure and tensile strength of the resultant joints were investigated. For the joint made with 0 mm-wide gap and without groove in steel side, severe incomplete brazing zone occurred along the steel side and bottom surfaces, and consequently seriously deteriorated the joint strength. However, presetting 1.5 mm-wide gap or with groove in steel side could promote the wetting of molten filler metal on the faying surfaces, and then significantly enhance the resultant joint strength. Moreover, post-weld heat treatment could further improve the tensile strength of the joints. During tensile testing, the specimens from the joints made with Al-12%Si flux-cored filler wire fractured through the weld or interfacial layer, but those from the heat-treated joints made with Zn-15%Al flux-cored filler wire fractured in the aluminum base metal.

KEY WORDS: Aluminum; Stainless steel; Arc-brazing; Gap width; Groove; Mechanical property

1. Introduction

Dissimilar metal joint between aluminum alloy and steel is widely used in automotive, aerospace and shipbuilding industries, because it combines the advantages of two metals, reduces the structure weight and improves the fuel efficiency^[1,2]. However, direct fusion-welding of aluminum alloy to steel is still a challenge due to the low solubility of Fe in Al at room temperature and the large differences in physical-thermal properties between the two materials^[3,4].

Recently, fusion-brazing, which can use electrical arc or laser beam as the heat source, with fusion welding on the aluminum side and brazing on the steel side, becomes an attracting research focus in joining aluminum alloy to steel^[5,6]. During fusion-brazing of aluminum alloy to uncoated steel with butt joint, the good wetting and spreading of the liquid metal

(including the molten aluminum base metal and molten filler metal) on steel surfaces, especially on the side and bottom surfaces, has to be guaranteed. Smearing non-corrosive flux on steel surfaces or using flux-cored filler metals are effective methods to promote the wetting and spreading of the liquid metal on uncoated steel surface^[5,7,8]. However, smearing non-corrosive flux on steel surfaces is time consuming and more complicated than using flux-cored filler metal alone since flux-cored arc welding combines the advantages of arc welding and brazing processes.

In this paper, butt joining of aluminum alloy to uncoated stainless steel were investigated using gas tungsten arc welding process with flux-cored filler metals, and the effects of gap width and groove on steel side on the appearance, microstructure and mechanical properties of the resultant joints were discussed. Meanwhile, the joints post-weld heat treated at 280 °C for 30 min were also tested for comparison.

2. Experimental

5A02 aluminum alloy and 304 stainless steel sheets

† Corresponding author. Assoc. Prof., Ph.D.; Tel: +86 411 84706283; Fax: +86 411 84709284; E-mail address: donghg@dlut.edu.cn. (Honggang DONG)

Table 1 Nominal compositions (wt.%) of 5A02 aluminum alloy and 304 stainless steel

Material		Composition						
5A02	Si0.40	Fe0.40	Cu0.10	Mn0.15-0.40	Mg2.0-2.8	Ti0.15	Al bal.	
304	C0.08	Si1.00	Mn2.00	P0.045	S0.030	Ni8.00–11.0	Cr18.00–20.0	Fe bal.

with dimensions of 200 mm×80 mm×1.5 mm were used as the base metals, and their nominal compositions are listed in Table 1. The filler wires, 1.8 mm in outer diameter, were Al-12%Si and Zn-15%Al alloys flux-cored with KAlF₄ and CsAlF₄, respectively. Butt joints were made on a backing copper plate with an 8 mm-wide and 1 mm-deep groove for the control of bead formation on the backside of the weld. An angular joint was used in order to investigate the effects of gap width on the microstructure and mechanical properties of the joints with “D” representing the gap width between the faying edges of two workpieces, as shown in Fig. 1. Moreover, a single groove with 45° bevel angle on steel side, as shown in

Fig. 1 Schematic diagram of the angular butt design with “D” representing the gap width between the end edges of two workpieces

Fig. 2, was designed to investigate the influence of the groove on the microstructure and mechanical properties of the resultant joints. Considering the joint deformation and diameter of the filler wire, primary trial experiments were conducted, consequently, the gap width was set as 0.3 mm with groove and 1.5 mm without groove existing on steel side.

Before welding, the workpiece was cleaned with acetone to remove grease or oil and brushed with a stainless steel brush to remove the oxide films on the faying surfaces. During welding, alternative current was used with argon as the shielding gas with a flow rate of 10 L/min, the wire feeding speed was 11 mm/s, the travel speed was 2 mm/s and the other welding parameters are listed in Table 2. After welding, the joints were post-weld heat treated in air in a furnace at 280 °C for 30 min and then cooled down in the furnace to room temperature. The microstructure of the joints and distribution of major alloying elements in the weld/steel interface were examined with optical microscopy (OM) and electron probe microanalysis (EPMA). The tensile strength was obtained from the average of three 25 mm wide specimens.

3. Results and Discussion

3.1 Cross-section and microstructure

Fig. 3 displays the cross-sections of 5A02 aluminum alloy/304 stainless steel joints. The images

Fig. 2 Schematic of the groove on steel side

Table 2 Welding parameters and the tensile strength of 5A02 aluminum alloy/304 stainless steel joints

Filler metals	Welding current/A	Gap width/mm	Groove*	Post-weld heat treatment	Average tensile strength/MPa
Zn-15%Al flux-cored filler wire	60	0	–	As-welded	87
		1.5	–	As-welded	157
		1.5	–	280°C, 30 min	199
		0.3	Y	As-welded	–
		0.3	Y	280°C, 30 min	198
Al-12%Si flux-cored filler wire	70	0	–	As-welded	54
		1.5	–	As-welded	125
		1.5	–	280°C, 30 min	149
		0.3	Y	As-welded	120
		0.3	Y	280°C, 30 min	131

*Note: “Y” stands for welding with groove, and “–” stands for welding without groove on steel side

show that both Zn-15%Al and Al-12%Si flux-cored filler wires had good wettability and flowability on the steel surfaces when the joints were made with 1.5 mm-wide welding gap or with a groove on the steel side. It can also be seen that Zn-15%Al flux-cored filler wire has better wettability and flowability than Al-12%Si flux-cored filler wire, as comparing Fig. 3(a) and Fig. 3(b). The large content of Zn in Zn-15%Al flux-cored filler wire, which has a low melting point, promoted the wetting and spreading of molten filler wire on steel surfaces^[9]. However, severe incomplete brazing zone occurred along the steel side and bottom surfaces when the joint was made with 0mm-wide gap and without groove on steel side, which was already described in previous work^[10] and will not be further discussed here.

Fig. 4 reveals the weld microstructure from the joints made with 1.5 mm-wide welding gap. It can be known from Fig. 4(a) that the weld with Zn-15%Al flux-cored filler wire was composed of Zn-rich solid solution (Zn), Al-rich solid solution (Al) and bright Zn-rich particles. After PWHT, the size of Zn-rich particles obviously increased, as comparing Fig. 4(a) and Fig. 4(b).

Fig. 5 displays the backscattered electron images of the interfacial layer from the joints made with Zn-15%Al flux-cored filler wire and 1.5 mm-wide welding gap. It can be seen that the thickness of the

interfacial layer on steel side surface was 4.5 μm in as-welded state and then increased to 5.7 μm after PWHT. The increase of interface thickness with Al-12%Si flux-cored filler wire and 1.5 mm-wide welding gap after PWHT also occurred^[10]. The mutual diffusion of alloying elements from the weld and steel during PWHT increased the thickness of the interfacial layer.

The results of EPMA elemental scanning analysis reveal that the interfacial layer from the joint made with Al-12%Si flux-cored filler wire and 1.5 mm-wide welding gap contained 9.366Si, 30.031Fe and 60.581Al (wt.%), and the corresponding phase could be $\text{Al}_{17.4}\text{Fe}_2\text{Si}^{[11]}$, which was also in accordance with that reported by Murakami *et al.*^[8]. For the interfacial layer from the joint made with Zn-15%Al flux-cored filler wire and 1.5 mm-wide welding gap, 30.973Fe, 61.997Al and 6.993Zn (wt.%) were detected, and the formed phase could be $[\text{FeAl}_3]\text{Zn}_x^{[12]}$.

Fig. 6 shows the microstructure of the interfacial layer from the heat-treated joint made with Zn-15%Al flux-cored filler wire and with groove on steel side. It can be seen that the interface thickness was uniformly 5–6 μm . The EPMA measurements reveal that the interfacial layer contained 53.656Al, 32.237Fe, 13.934Zn and 0.173Mg (wt.%), and the corresponding phase could be $[\text{FeAl}_3]\text{Zn}_x^{[12]}$.

Fig. 3 Cross-sections of the post-weld heat treated 5A02 aluminum alloy/304 stainless steel joints with (a) Zn-15%Al flux-cored filler wire and 1.5 mm-wide gap; (b) Al-12%Si flux-cored filler wire and 1.5 mm-wide gap^[10]; (c) Zn-15%Al flux-cored filler wire and groove on steel side; (d) Al-12%Si flux-cored filler wire and groove on steel side

Fig. 4 Microstructure of welds from 5A02 aluminum alloy/304 stainless steel joints made with: (a) Zn-15%Al flux-cored filler wires, as-welded; (b) Zn-15%Al flux-cored filler wires, PWHT

Fig. 7 displays the microstructure of the interfacial layer from 5A02 aluminum alloy/304 stainless steel joints made with Al-12%Si flux-cored filler wire and with groove on steel side. It can be seen that the

thickness of the interfacial layers from the joints in as-welded and PWHT states was uniform and thinner than $10\ \mu\text{m}$. The EPMA analysis reveals that the interfacial layer consisted of 63.575Al, 18.202Fe,

Fig. 5 Backscattered electron images of the interfacial layer on steel side surface from 5A02 aluminum alloy/304 stainless steel joints made with Zn-15%Al flux-cored filler wires in as-welded (a) and PWHT state (b)

Fig. 6 Microstructure of the interfacial layer from heat-treated 5A02 aluminum alloy/304 stainless steel joints made with Zn-15%Al flux-cored filler wire and with groove on steel side: (a) on top surface; (b) on side surface; (c) on bottom surface

Fig. 7 Microstructure of the interfacial layer from 5A02 aluminum alloy/304 stainless steel joints made with Al-12%Si flux-cored filler wire and with groove on steel side: (a) on top surface, as-welded; (b) on side surface, as-welded; (c) on bottom surface, as-welded; (d) on side surface, PWHT

Fig. 8 Fracture positions in 5A02 aluminum alloy/304 stainless steel joints during tensile testing: (a) and (b) Al-12%Si flux-cored filler wire, 1.5 mm-wide gap, as-welded; (c) Al-12%Si flux-cored filler wire, groove on steel side, as-welded; (d) Zn-15%Al flux-cored filler wire, 1.5 mm-wide gap, PWHT

18.121Si and 0.102Mg (wt.%).

3.2 Tensile strength

The tensile testing results listed in Table 2 shows that presetting 1.5 mm-wide welding gap or making groove on steel side could significantly promote the tensile strength of the resultant joints. When using Al-12%Si flux-cored filler wire, the average tensile strength of the as-welded joints with 1.5 mm-wide welding gap and with groove on steel side was 125 MPa and 120 MPa, and increased to 149 MPa and 131 MPa after PWHT, respectively. When using Zn-15%Al flux-cored filler wire, the average tensile strength of the as-welded joint with 1.5 mm-wide welding gap was 157 MPa, much higher than that of the joints with Al-12%Si flux-cored filler wire. However, cracks occurred along the weld from the as-welded joint made with groove on steel side. After PWHT, the average tensile strength of the resultant joints with 1.5 mm-wide welding gap and with groove on steel side reached around 200 MPa.

During tensile testing, all specimens from the joints made with Al-12%Si flux-cored filler wire fractured in the weld or through the weld/steel interface as shown in Fig. 8(a), Fig. 8(b) and Fig. 8(c). The as-welded specimens made with Zn-15%Al flux-cored filler wire and with 1.5 mm-wide welding gap fractured through the weld/steel interface. However, the heat-treated joints made with Zn-15%Al flux-cored filler wire fractured in the aluminum base metal, as shown in Fig. 8(d). For the joints made with Al-12%Si flux-cored filler wire, crack during tensile testing originated on steel bottom surface due to the thick $\text{Al}_{7.4}\text{Fe}_2\text{Si}$ intermetallic compound layer^[10], and then propagated along the side surface, as illustrated by the arrows in Fig. 8(b). After the crack propagated to the up corner of steel, it expanded along the weld or steel top surface owing to the stress concentration at the corner^[10]. The better wetting and spreading of Zn-15%Al flux-cored filler wire on steel surfaces than Al-12%Si flux-cored filler wire increased the bonding area to bear the tensile load. After PWHT, the residual stress in the joints could be reduced or even eliminated, which would help to enhance the joint strength.

The tensile testing results also display that the tensile strength of the as-welded joints made with 1.5 mm-wide welding gap and with groove on steel side was around 120 MPa when using Al-12%Si flux-cored filler wire. Meanwhile, cracks happened more easily in the as-welded joint with groove on steel side when using Zn-15%Al flux-cored filler wire. However, making groove was more complicated and time consuming than only presetting welding gap. Thus, presetting welding gap is a more efficient approach to promote the wetting and spreading of molten filler metal on steel surfaces and increase the joint strength.

4. Conclusions

(1) Presetting 1.5 mm-wide gap or making groove on steel side could promote the wettability and flowability of molten filler metals on steel surfaces, avoid the formation of incomplete brazing zone and then significantly enhance the joint strength. While keeping other welding parameters constant, presetting welding gap is a more efficient approach than making groove on steel side alone to promote the wetting and spreading of molten filler metals on steel surfaces and consequently increase the joint strength, considering the manufacture cost and actual extent of strength improvement.

(2) When using Al-12%Si flux-cored filler wire, the tensile strength of the as-welded joints made with 1.5 mm-wide welding gap or with groove on steel side kept at around 120 MPa, but it slightly increased after PWHT. When using Zn-15%Al flux-cored filler wire, the heat-treated joints made with 1.5 mm-wide welding gap or with groove on steel side reached about 200 MPa. During tensile testing, the heat-treated joints made with Zn-15%Al flux-cored filler wire fractured in aluminum base metal, and all other joints fractured in the weld or through the weld/steel interface.

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