Laser-MIG Arc Hybrid Brazing-Fusion Welding of Al Alloy to Galvanized Steel with Different Filler Metals

Shujun WANG, Guoliang QIN[†] and Yuhu SU

Key Laboratory for Liquid-Solid Structure Evolution and Processing of Materials, Ministry of Education, Shandong University, Jinan 250061, China

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Aluminum alloy plates were joined to galvanized steel sheets with lap joint by laser-MIG arc hybrid brazing-fusion welding with AlSi5, AlSi12, AlMg5 filler wires, respectively. The influences of Si and Mg on the microstructure and mechanical properties of the brazed-fusion welded joint were studied. The increase of Si element in the fusion weld can make the grain refined, and increase the microhardness of the fusion weld. Therefore, the microhardness in fusion weld made from AlSi12 and AlSi5 filler wires can be up to 98.4 HV0.01 and 96.8 HV0.01, which is higher than that from AlMg5 filler wire of 70.4 HV0.01. The highest tensile strength can reach 178.9 MPa made with AlMg5 filler wire. The tensile strength is 172.43 MPa made with AlSi5 filler wire. However, the lowest tensile strength is 144 MPa made with AlSi12 filler wire. The average thicknesses of the intermetallic compounds (IMCs) layer with AlSi5, AlSi12, AlMg5 filler wires are 1.49–2.64 μm . The IMCs layer made from AlSi5, AlSi12 filler wires are identified as FeAl_2 , Fe_2Al_5 , $\text{Fe}_4\text{Al}_{13}$ and $\text{Al}_{0.5}\text{Fe}_3\text{Si}_{0.5}$, that from AlMg5 filler wire are identified as FeAl_2 , Fe_2Al_5 and $\text{Fe}_4\text{Al}_{13}$.

KEY WORDS: Hybrid welding; Welding of dissimilar metals; Aluminum alloy; Galvanized steel; Mechanical properties; Intermetallic compounds

1. Introduction

There has been a growing requirement of welded structures made of dissimilar metals between aluminum alloy and steel for weight reduction and energy saving^[1]. However, the fusion joining of aluminum alloy to steel meets difficulties because of the large differences in thermo-physical properties between aluminum and iron, and the brittle and hard Fe-Al intermetallic compounds (IMCs) such as FeAl_3 , Fe_2Al_5 and so on formed in fusion welded joint deteriorate the mechanical properties of the fusion welded joints of Al alloy and steel^[1,2–6].

According to the difference in melting point between Al alloy and galvanized steel, the brazing-fusion welding process was developed to realize joining of Al alloy and galvanized steel with the high efficiency

and high quality^[7]. In brazing-fusion welding process, by applying the proper welding heat input, the galvanized steel will not be molten for its higher melting point. The filler metal and the base metal of Al alloy will be molten because of their lower melting point and will form the fusion welded joint. The molten Al alloy including filler metal and Al alloy base metal will spread on the top surface of the galvanized steel and form the brazed joint. The welding process has the characteristics of fusion welding and brazing. In brazing-fusion welding process, the proper and stable energy input is necessary to make sure that the steel plate is not melted. Because laser-MIG arc hybrid welding has stable welding process and outputs the constant welding energy, it was used to realize the high efficient and high quality brazing-fusion welding of Al alloy to steel plate^[8].

The diffusion and reaction between Al and Fe can be adjusted by adding some elements such as Cu, Zn or Mn in the metal^[1,2,9,10]. In addition, the addition of Si into brazed seam can improve the wettability of the filler metal on the base metal and inhibit the

[†] Corresponding author. Assoc. Prof., Ph.D.; Tel: +86 13505400905; Fax: +86 531 88392711; E-mail address: glqin@sdu.edu.cn (Guoliang QIN)

growth of IMCs.

In this paper, the influences of the addition of Si and Mg on the microstructure characteristics and mechanical properties of the brazed-fusion welded joint were studied with laser-MIG arc hybrid brazing-fusion welding of aluminum alloy to galvanized steel with AlSi5, AlSi12, AlMg5 filler wires, and its influences on the intermetallic compounds were emphatically analyzed.

2. Experimental

The lap joints were prepared by laying 5A02 Al alloy plate with 1.0 mm in thickness on the galvanized steel plate of 2.0 mm in thickness, were welded by Nd: YAG laser-MIG arc hybrid brazing-fusion welding process, the schematic diagram is shown in Fig. 1. The overlap width is 10 mm. The dimensions of base materials are 200 mm×50 mm. The chemical compositions of base materials are shown in Table 1. The filler wires used in the experiments were AlSi5, AlSi12 and AlMg5 of 1.2 mm in diameter. Their chemical compositions are also shown in Table 1. The joining process was performed with digital MIG arc welding power supply and Nd: YAG solid state laser oscillator at the same parameters of 3 m/min in welding speed, 4 m/min in wire feeding rate, 1000 W in laser power. Laser beam is leading to the MIG arc, the laser-wire distance is 4 mm, which indicates the distance from the center of laser spot to that of MIG arc. In welding process, Argon gas was used as the shielding gas with the flow rate of 16 L/min.

Before welding, sandpaper was used to remove the oxide film on the top surface of Al alloy plate, and the acetone was used to wipe off oil stain and sand particles on the Al alloy plate. The acetone was also used to remove oil stain on the top surface of galvanized steel plate.

The microstructures in the brazed-fusion welded joint were analyzed with metallographic microscope. The IMCs on the brazed interface were analyzed by scanning electron microscopy (SEM) with an energy-dispersive spectrometer (EDS) and X-ray diffraction (XRD) analysis. The microhardness from the base metal of Al alloy to fusion weld was tested with the DHV-1000 digital microhardness tester with a load of 0.1 N and a loading time of 10 s. Three transverse

tensile specimens of 90 mm in length and 15 mm in width were prepared from each welding specimens and the tensile strengths of the brazed-fusion welded joint at room temperature were evaluated at a cross head speed of 1 mm/min, and the fracture appearance were analyzed by SEM analysis.

3. Results and Discussion

Fig. 2 shows morphology of brazed-fusion welded joint of Al alloy and galvanized steel. The brazed-fusion welded joint is composed of fusion welded joint and brazed joint as shown in Fig. 2, the microstructures of fusion welded joint and brazed joint are different, so it is very necessary separately analyzed.

3.1 Microstructures

Fig. 3 shows the microstructures near the fusion zone of the fusion weld with AlSi5, AlSi12 and AlMg5 filler wires, respectively. It can be indicated that the nucleation and growth of the grains in the fusion weld based on the base metal of Al alloy, so a columnar grain zone near the fusion line grew and the width of this zone is different for different filler wires. With the increase of Si element in the filler wire, the columnar grain zone was thinner and the grains were finer, as shown by comparing Fig. 3(a) with Fig. 3(b). However, the dendrite directly grew up along the Al alloy base metal without shaping apparent heat affected zone (HAZ) and columnar crystal zone around the fusion boundary when AlMg5 filler wire was used, shown in Fig. 3(c).

The microstructures in the fusion weld made from three filler wires are shown in Fig. 4. The analyzed results show that, the fusion weld with Al-Si filler wires was consisted of α -Al solid solution equiaxed grains

Fig. 1 Schematic diagram of laser-MIG hybrid brazing-fusion welding process

Table 1 Chemical composition (wt.%) of base metals and filler metals

Material	C	Si	Mg	Fe	Mn	Cu	Ti	Zn	—	S	P	Al
Aluminum	—	0.40	2.0-2.8	0.40	0.15-0.40	0.10	0.15	—	—	—	—	Bal.
Galvanized steel	0.050	0.020	—	Bal.	0.60	—	—	—	0.05-0.20	0.019	0.0090	—
AlSi5	—	4.5-6.0	0.05	0.8	0.05	0.30	0.20	0.10	—	—	—	Bal.
AlSi12	—	11.0-13.0	0.10	0.8	0.15	0.30	—	0.20	—	—	—	Bal.
AlMg5	—	0.25	4.5-5.5	0.40	0.20-0.50	0.10	0.06-0.20	0.10	0.05-0.20	—	—	Bal.

and short rod-like Al-Si eutectics at grain boundary. However, there is no obvious grain boundary in fusion weld with Al-Mg filler wire, its weld is consisted of α -Al solid solution and the precipitated phase of β -Mg₂Al₃. By comparing Fig. 4(a) and Fig. 4(b), it can be shown that more Al-Si eutectics are found in grain boundary in fusion weld with AlSi12 filler wire than that with filler wire AlSi5. With the increase of Si element in the fusion weld, more Al-Si eutectics were formed at grain boundary. Moreover, it can be found that the size of equiaxed grain with AlSi12 filler wire is finer than that with AlSi5, which indicates that the Si element can make the grain refined.

Fig. 2 Morphology of brazed-fusion welded joint of Al alloy to galvanized steel

3.2 Brazed seam

Fig. 5 shows EDS analysis on the distribution of Al, Fe, Si and Mg elements across the brazed interface with filler wire AlSi5, AlSi12 and AlMg5. From Fig. 5, it can be shown that the average thickness of IMCs layer is less than 10 μ m. Generally, the IMCs layer is not good for the mechanical properties of the joint^[5]. However, a visible unequal thickness IMC layer is formed in the brazed interface with different filler wires. The average thickness of IMCs layer with AlSi5 filler wire is about 1.49 μ m, while that with AlSi12 and AlMg5 filler wires are about 0.90 μ m and 2.64 μ m, respectively. It is found in Fig. 5 that Fe diffuses into the brazed seam, and the diffusion amount of Fe with AlSi12 filler wire is less than that with AlSi5 filler wire by comparing Fig. 5(a) and Fig. 5(b). So the diffusion of Fe into the brazed seam is effectively suppressed with higher Si content in the filler wire. Therefore, it is obvious that the increase of Si content in filler wire can suppress the growth of IMCs layer. However, the amount of Fe with AlMg5 filler wire, as shown in Fig. 5(c) was obvious more than that with Al-Si filler wires shown in Fig. 5(a) and Fig. 5(b). So

Fig. 3 Microstructure near fusion zone in fusion welded joint with different filler wires: (a) AlSi5, (b) AlSi12, (c) AlMg5

Fig. 4 Microstructure in fusion weld with different filler wires: (a) AlSi5, (b) AlSi12, (c) AlMg5

Fig. 5 EDS analysis of brazed seam with different filler wires: (a) AlSi5, (b) AlSi12, (c) AlMg5

this result also confirms that the additions of Si in the filler wires can effectively control the growth of the Al-Fe IMCs layer during welding process of Al alloy to galvanized steel.

Fig. 6 shows X-ray diffraction results of the IMCs layer on the Al alloy side made from filler wire AlSi5, AlSi12 and AlMg5, respectively. The IMCs layer made from AlSi5 filler wire are identified as FeAl_2 , Fe_2Al_5 , $\text{Fe}_4\text{Al}_{13}$ and $\text{Al}_{0.5}\text{Fe}_3\text{Si}_{0.5}$, which is the same with that using AlSi12 filler wire. From the above mentioned that Si element in the filler wires can effectively control the growth of the Al-Fe IMCs layer, it can be found that the element of Si in the filler metals can effectively control the growth of the Al-Fe IMCs by replacing Al-Fe binary phases with Al-Fe-Si ternary phases^[11–13]. However, the IMCs layer with AlMg5 filler wire is identified as FeAl_2 , Fe_2Al_5 and $\text{Fe}_4\text{Al}_{13}$, as shown in Fig. 6 (c). The results that the amount of diffusion is in the interface layer agree with the EDS analysis of the steel/seam interface layer obtained in line scanning.

Fig. 7 shows the tensile strength of the brazed-fusion joint with different filler wires. The highest tensile strength can reach 178.9 MPa for AlMg5 filler wire, and the tensile strength can be up to 172.43 MPa and 144 MPa for AlSi5 and AlSi12 filler wires, respectively. It is obvious that the increase of Si

content in filler wire is not good for the tensile strength of the brazed-fusion welded joint, and Mg element in filler wire is good for the tensile strength of the brazed-fusion welded joint. In tensile test, the fracture location occurs at HAZ of Al alloy or fusion weld as shown in Fig. 8. The fracture appearances are shown in Fig. 9. The fracture surface of specimens which has occurred in the aluminum HAZ is shown in Fig. 9(a) shows that the fracture at the HAZ of Al alloy is a typical ductile fracture. Fig. 9(b) shows that there are many pores in fusion weld.

Fig. 7 Tensile strength of the joint made with different filler wires

Fig. 6 X-ray diffraction results of IMCs layers on aluminum side with different filler wires: (a) AlSi5, (b) AlSi12, (c) AlMg5

Fig. 8 Fracture location at HAZ (a) and fusion weld (b)

Fig. 9 Fracture appearance at HAZ (a) and fusion weld (b)

Fig. 10 Microhardness profile across weld/aluminum interface

Fig. 10 shows the microhardness distribution from the base metal of Al alloy to the fusion weld, which shows that the microhardness increases from Al alloy to fusion weld. Moreover, it also can be found that the microhardness in the fusion weld made from AlSi12 and AlSi5 filler wires can reach 98.4 HV_{0.01} and 96.8 HV_{0.01}, which is much higher than 70.4 HV_{0.01} of the fusion weld made from AlMg5 filler wire. Therefore, on the one hand, the fine grain size can lead to the fine grain strengthening that play a certain improvement on the microhardness of the fusion weld. On the other hand, the formation of the harder Al-Si eutectic mixture can make the microhardness of the fusion weld significantly increased.

4. Conclusions

(1) 5A02 Al alloy plates was lap jointed to galvanized steel sheets by Nd: YAG laser-MIG arc hybrid brazing-fusion welding with AlSi5, AlSi12 and AlMg5 filler wires.

(2) The increase of Si element in the fusion weld can make the grain refined, and more Al-Si eutectics were formed in grain boundaries, which make a certain improvement on the microhardness of the fusion weld.

(3) The average thicknesses of the IMCs layer with AlSi5, AlSi12 and AlMg5 filler wires are 1.49–2.64 μm. The IMCs layer with AlSi5, AlSi12 filler wires are identified as FeAl₂, Fe₂Al₅, Fe₄Al₁₃ and Al_{0.5}Fe₃Si_{0.5} however, that with AlMg5 filler wire are identified as FeAl₂, Fe₂Al₅ and Fe₄Al₁₃. Si additions in the filler wires effectively control the growth of the Al-Fe IMCs layer by replacing Al-Fe binary phases with Al-Fe-Si ternary phases.

(4) The microhardness in the fusion weld made from AlSi12 and AlSi5 filler wires are 98.4 HV_{0.01} and 96.8 HV_{0.01}, which are much higher than 70.4 HV_{0.01} of that with AlMg5 filler wire. The tensile strength can reach 178.9 MPa for AlMg5 filler wire and 172.43 MPa made from AlSi5 filler wire, while the tensile strength is only 144 MPa for the fusion weld with AlSi12 filler wire. The increase of Si content in filler wire can reduce the tensile strength of the brazed-fusion welded joint.

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