Effects of activating flux on aluminum alloy to steel butt-joint using a MIG weld-brazing process

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Abstract

A novel metal inert gas (MIG) weld-brazing was employed to produce the dissimilar materials butt-joint welds that specimens consisted of 6061 aluminum (Al) alloy and galvanized steel sheet. In this process, the fluxes such as CaF_2 , TiO_2 , SiO_2 and ZnO powder were coated on the surface of steel respectively to investigate the effect of activating fluxes on the performance of specimens. The experimental results revealed that CaF_2 flux powder was applied as a suitable flux which spreadability of filler material on steel surface become better. In order to obtain better appearances of specimen surface, the coating thickness of flux powder should be accurately control at 0.1 mm. When SiO_2 flux powder was coated on surface of specimen, the amount and the size of porosity decrease simultaneously in the fusion zone (FZ) of weld bead. It led to improve the tensile strength of Al/steel butt-joint specimens. The surface of specimens coating with CaF_2 , TiO_2 or SiO_2 flux powder, the thicknesses of intermetallic compound (IMC) layer were less than 10 μm . The specimens produced by coating with ZnO flux may increase the temperature of FZ, the average thickness of IMC layer was 14.62 μm and the IMC layer presents a saw tooth shape.

Keywords : Metal inert gas (MIG) welding, Brazing, Activating flux, Aluminum, Galvanized steel

1.Introduction

Compared with the low-carbon steel sheet, use of Al alloys as automotive parts has many advantages such as higher weight-strength ratio and recoverability. The reduction of fuel utilization could be accomplished by using light materials such as Al panels and body frame of the vehicles. The vehicle structures adopt Al alloys that could lead to weight reduction and energy saving. Due to the outstanding resist of corrosion, the galvanized steel sheet has been extensively employed by the automotive industry as well. The dissimilar materials joining performance of Al alloy and galvanized steel sheet has been paid growing attention in manufacturing industries (Zhang et al. 2013). The brittle intermetallic compounds (IMCs) are formed between the interface of Al and steel during welding process, it is difficult to achieve a proper joint of Al/steel by means of the traditional arc welding process (Lin et al. 2018). Therefore, Chen et al. (2019) utilized the friction stir welding process to produce the lap joints of 6061 Al alloy and steel sheet. When the welding parameters were set at optimal conditions, the maximum failure load of specimen was achieved at 2.26 kN. Dong et al. (2016) employed the refilled friction stir spot welding process to produce the lap joints of Al alloy and steel sheet. When the welding parameters were set at optimal conditions, the maximum tensile-shear fracture load of specimen was achieved at 3.044 kN. All of the tensile-shear testing specimens failed at the interface between Al and steel. Lü et al. (2018) used the laser fusion weld-brazing process to produce the lap joints of Al/steel. When the welding parameters were set at optimal conditions, the maximum tensile fracture load of specimen was achieved at 152.5 MPa. Wider lap interface between Al and steel, and narrow heat affect zone (HAZ) were formed by employing this laser weld-brazing process. However, these novel weld-brazing processes have disadvantage of either lacking versatility or high cost.

The MIG weld-brazing process has been recommended to obtain higher quality of joints between Al and steel that using appropriate heat input to melt Al alloy but maintain the steel in solid state. Shao et al. (2015) adopted a pulsed double electrode MIG welding process to generate the joint of Al/steel. The low heat input was used to the specimen that

was finalized by varying the bypass current in this novel welding process. When the heat input reduced, the amount of IMC phases gradually decreased. Ye et al. (2017) employed the MIG-TIG double-sided arc welding process to generate butt joint of Al/steel. When the MIG voltage enhances, the thickness of IMC layer increases at the interface between Al and steel. The appearance of weld bead and interface between Al and steel significantly impact the tensile strength of the Al/steel butt-joint welds, and the tensile strength of specimen was achieved at 150 MPa in this process. Basak et al. (2016) used a pulsed MIG weld-brazing process to produce the lap-joint of Al/steel. When the welding parameters were set at optimal conditions, the maximum tensile fracture load of specimen was achieved at 243 MPa. Due to the surface protection, Zn coating is necessary for Al alloy and steel joining, the metallic characteristic after evaporation of Zn rather than the oxidic characteristic for un-galvanized steel.

Based on the above research, Zn is an unstable factor that needs to be avoided by a reasonable design in the weld-brazing process (Lin et al. 2016). Therefore, Qin et al. (2017) developed a fluoride flux that coated on surface of steel may improve the spreadability of filler materials. The fluoride flux floating on the surface of welding pool that weakened the surface tension in the FZ and then reduced the evaporation of Zn. It led to enhance the mechanical property of the dissimilar materials butt-joint welds greatly. When the activating flux was set at optimal component, the maximum tensile fracture load of specimen was achieved at 120 MPa. Goecke et al. (2019) demonstrated that increase the MIG welding heat input, the porosity in FZ reduce. It attributed to efficient escape of Zn-vapor from the molten bead deposit between Al and steel. When the welding heat input was set at optimal conditions, the maximum tensile fracture load of specimen was achieved at 1.82 kN. In additions, Huang et al. (2007) investigated the effects of arc constriction on the penetration of welds, the SiO₂ flux powder was coated on the surface of Al base metal. The experimental results demonstrated that SiO₂ flux powder was coated on the surface of Al base metal could make the welding arc to be constricted. Therefore, it led to the high melting temperature and boiling temperature resistively in fusion zone of the process. Based on above technical literature, the object of this work is to investigate the effects of fluxes such as CaF₂, TiO₂, SiO₂ and ZnO powder on appearance of specimen surface and microstructure of weld bead, porosity of FZ, IMC layer of interface and mechanical property of specimens during MIG weld-brazing process.

2. Materials and experimental procedure

In this MIG weld-brazing process, 6061 Al alloy and galvanized steel sheets were selected as base metals. The dimensions of Al alloy and galvanized steel sheets were 180 mm × 50 mm × 3.0 mm and 180 mm × 70 mm × 1.2 mm, respectively. The diameter 1.6 mm ER4043 filler wire was chosen as the filler material. The chemical composition of Al alloy, steel sheet and filler material are listed in Table 1.

Table 1. Chemical content of base metals and filler material

Components, Wt. %	C	Si	Mn	P	S	Fe	Zn	Mg	Cu	Cr	Ti	Al
Galvanized steel	0.02	0.01	0.18	0.03	0.01	Bal.	-	-	-	-	-	-
6061 Aluminum	-	0.6	0.15	-	-	0.7	0.25	1.2	0.15	0.25	0.15	Bal.
4043 filler wire	-	5	0.05	-	-	0.8	0.1	0.05	0.3	-	0.2	Bal.

The experimental procedure that produce a butt-joint specimen consist of 6061 Al alloy and steel sheet, the root opening between Al alloy and steel sheet was fixed at 0.4 mm. Before the process, the oxide layer on the surfaces of 6061 Al alloy plate was polished by using a sanding machine. In additions, the flux powders that selected by the authors were mixed with methanol (CH₃OH) to produce a paint-like consistency, as shown in Fig.1a and 1b. Four single-component activating fluxes such as CaF₂, TiO₂, SiO₂ and ZnO powder were coated on the surface of galvanized steel sheet using a brush, respectively. As shown in the Fig.1c, four types of activating flux powder were coated on the surface of galvanized steel sheet. In the experiment of this study, the thickness of activating flux powder was accurately control at 0.1 and 0.3 mm by mean of using different proportion solute between methanol and activating flux powder. The MIG welding machine (Horbart Mega-Pluse MPI-350) and the welding torch can be set at different speeds was utilized to produce a butt-joint specimen. The travel speed of MIG torch was set at 270 mm/min, and the MIG welding voltage and the feed of filler wire were set at 17 V and 91 mm/sec respectively. Based on these MIG welding parameters, the welding current

was regulated between 18 and 21A during the MIG arc brazing process which using different activating flux powder. This study utilized argon (Ar) as the shielding gas and the flow rate was set at 17.5 L/min. After MIG weld-brazing process, three tensile strength testing specimens with 10 mm-wide were cut from each dissimilar materials butt-joint weld. The surface condition of specimens, cross-section, microstructure and porosity of weld bead, the thickness of IMC layer in the FZ were investigated by the optical microscope (OM) and scanning electron microscope (SEM).

Fig. 1 Schematic diagram of coating method and MIG weld-brazing process using the activating flux.

3. Results and discussions

3.1 Effect of flux thickness on surface of specimens

The appearances of specimen surface that four types of activating flux powder were coated with 0.3 mm thickness on the surface of steel sheet as shown in Fig. 2. The specimens that coated with CaF_2 , TiO_2 , SiO_2 and ZnO powder, the weld beads of specimen surface are incomplete and numerous spatters. This is in accord with the research that implemented by the author in the previous experimental results (Lin et al. 2014 and Lin 2017). It demonstrated that the surface of 6061 Al alloy coated with about 0.3 mm 100% SiO_2 flux powder presents narrower weld width and spatters because of high melting temperature and arc constriction on the top of MIG weld pool. Therefore, the specimen that coated with SiO_2 flux powder presents narrower weld width and many spatters as shown in Fig. 2c.

Qin et al. (2017) demonstrated that a modified flux consists from 73.6 wt.% KAlF_4 + 18.4 wt.% K_3AlF_6 + 8 wt.% K_2SiF_6 , which floats on the weld pool surface and Zn is avoided to be directly heated by the MIG arc. It led to that the evaporation of Zn is decreased and liquid Al filler material can spread on the surface of steel well, the joint strength can

reach up to 120 MPa. Qin et al. (2017) showed that the specimen coated with 100 wt.% KAlF_4 flux had the best spreadability of filler metal, the width of Al alloy weld bead was 6.6 mm approximately. As shown in Fig. 3, the specimen surface that four types of activating flux powder were coated with 0.1 mm thickness on the surface of steel. The specimens coated with thin layer of flux powder, the appearances of weld bead are complete and very few spatters, the width of Al alloy weld bead is 6.5 mm approximately. This experimental results revealed that the outcome of specimens coating with CaF_2 , TiO_2 , SiO_2 or ZnO powder were similar to that coated with a modified flux developed by the Qin et al. (2017). In order to obtain higher quality of Al/steel dissimilar materials butt-joint welds, the thickness of activating flux should be accurately control.

Fig. 2 The appearances of specimen surface coated with 0.3 mm flux powder.

Fig. 3 The appearances of specimen surface coated with 0.1 mm flux powder.

3.2 Effect of flux on spreadability of weld bead

Fig.4 shows the variations of the FZ and weld bead (WB) geometry that the surface of galvanized steel sheet coated with 0.1 mm thickness of CaF_2 and SiO_2 flux powder. The thickness of Al alloy and galvanized steel base metal (BM) were 3 mm and 1.2 mm, respectively. As shown in Fig. 4a, the OM images reveal that the CaF_2 flux powder was applied

as a suitable flux for the dissimilar materials butt-joint welds. Qin et al. (2017) showed that both the spreadability of filler material on galvanized steel surface and the weld appearance become better after specimens coating with KAlF_4 flux powder. The experimental results revealed that the fluoride powder was suggested to examine an activating flux for butt-joint of Al/steel butt-joint. In summary, the outcome of specimens coating with CaF_2 powder was similar to that coated with KAlF_4 flux powder developed by the Qin et al. (2017). the dissimilar materials butt-joint welds that produced by coating with SiO_2 flux powder appears the deeper penetration in the FZ of weld bead. In a previous research (Lin et al. 2017) developed by the author, the Marangoni convection has been proposed to explain the mechanism that increases the penetration of MIG welds produced by coating with SiO_2 flux powder on the surface of Al alloy base metal. The Marangoni convection could explain the deeper penetration of weld bead that specimen produced by coating with SiO_2 flux powder. However, it may decrease spreadability of filler material on the steel surface during MIG weld-brazing.

Fig. 4 The cross-section of welds coated with CaF_2 and SiO_2 flux powder.

3.3 Effect of flux on microstructure of fusion zone

Ruan et al. (2012) revealed that the penetration of welds produced by employing a twin wire MIG welding process using SiO_2 flux powder was about 26% deeper than that of the welds prepared without any activating flux. The arc constriction and higher arc temperature were the main reasons for increased penetration. Due to the higher arc temperature, the grain size of specimens coated with SiO_2 flux coarser than that of the welds prepared without any activating flux. In additions, it demonstrated that the specimens coated with SiO_2 flux powder did not have obvious effect on the mechanical properties of Al alloy welds.

The microstructure of FZ that the specimens coated with SiO_2 flux powder and without activating flux is shown in Fig.5. Generally, the FZ that specimens produced by employing 4043 Al-Si filler wires was consisted of short rod-like Al-Si eutectics in grain boundaries and α -Al solid solution dendrites (Dong et al. 2012). The α -Al solid solution of FZ made with 4043 filler wire that includes very few Al-Si eutectics in the entire welds as shown in Fig.5. In additions, a columnar crystal zone around the FZ is similar to the specimens that produced by SiO_2 flux powder and without activating flux on the surface of galvanized steel sheet. When SiO_2 flux powder was coated, the grains were coarser obviously than others as shown in Fig. 5b. The results are similar to the specimens that produced by Ruan et al. (2012).

Fig. 5 Effect of activating flux on microstructure of weld bead.

3.4 Effect of flux on tensile strength of specimens

The tensile strength of specimens that produced by traditional process without coated with flux and coated with CaF_2 , TiO_2 , SiO_2 and ZnO flux powder under the same MIG weld-brazing conditions were obtained as shown in Fig.6. For each activating flux powder, three sampling specimens were used to estimate the tensile strength of welds. Compare with the specimens coated with activating flux, the average tensile strength of welds that specimens coated with the four types flux powder selected by authors were better than that without coating any flux powder. The experimental results indicated that the traditional MIG weld-brazing process without use of activating flux, the average tensile strength of welds was 107.3 MPa. However, the surface of galvanized steel sheet coated with CaF_2 , TiO_2 , SiO_2 and ZnO flux powder, the average tensile strength of welds was 137.8, 128.6, 160.6 and 130.3 MPa, respectively. The tensile strength of specimens that coated with activating flux powder was measured higher than 107.3 MPa. When the surface of galvanized steel sheets coated with SiO_2 flux powder, the dissimilar materials butt-joint weld has the highest tensile strength. During the tensile testing process, all specimens fractured through the FZ of dissimilar materials butt-joint welds. It demonstrated that the four types flux powder were coated on the surface of steel with 0.1 mm thickness could improve the tensile strength of welds. Based on the comparison of the results as shown in Fig.6 and the microstructure of fusion zone as shown in Fig.5, it was found that the grain size of FZ is not a main factor that affect the tensile strength of specimens in this study.

Fig. 6 Tensile strength of specimens produced by coating flux.

3.5 Effect of flux on porosity in the fusion zone

The fractured surfaces for the tensile strength testing specimens at 40 magnifications are shown in Fig. 7. The amount of porosities that specimen produced by coating with CaF_2 and SiO_2 flux powder are less than TiO_2 and ZnO . It demonstrated that the tensile strength of specimen produced by coating with CaF_2 and SiO_2 flux powder higher than the others. Goecke et al. (2019) showed that the porosity in the FZ reduce with increase the welding heat input. It attributed to efficient escape of Zn-vapor from the molten bead deposit. Due to the higher arc temperature [15], the grain size of specimens that coated with SiO_2 flux coarser than that of the specimens produced without any activating flux as shown in Fig.5. As shown in Fig.6, the surface of steel sheet coating with the four types of flux powder, the average tensile strength of specimens improves. The tensile strength of specimens that the surface of steel sheet coated with SiO_2 flux powder is the highest. In summary, the tensile strength of aluminum alloy to steel butt-joint specimens attributed to the amount and size of porosity in the FZ. The fractured surfaces of specimens that executed the tensile strength testing are shown in Fig. 7. Due to the fracture occurred in the FZ that consist of 6061 Al alloy and 4043 filler material, the fractured surfaces were represented with dimple semblance that illustrated the ductile fracture. Many of porosities appear on fractured surfaces that belongs to the FZ of weld bead. When the surface of galvanized steel sheet coating with the CaF_2 , TiO_2 or ZnO flux powder, specimens increase the amount of porosity in the FZ, which contain about 15%, 23% and 20

% porosities of FZ respectively as shown in Fig.8a, 8b and 8d. It decreases the tensile strength of the Al/steel butt-joint specimens as shown in Fig.6. When the surface of galvanized steel sheet coating with the SiO_2 flux powder, the heat inputs cause efficient escape of Zn-vapor from the molten bead deposit, specimen decreases the amount and size of porosity, which contain only 3 % porosities of FZ as shown in Fig.8c. Therefore, the tensile strength of the Al/steel butt-joint specimens improves.

Fig. 7 Fracture surface of specimens at 40 magnifications.

Fig. 8 Fracture surface of specimens at 200 magnifications.

3.6 Effect of activating flux on interfacial reaction layers

Yagati et al. (2014) revealed that the thickness of IMC layer between Al alloy and steel is less than $10\ \mu\text{m}$, the interface between Al and steel is stable. During the brazing process, the thickness of IMC layer varied with heat input.

When the thickness between 8 and 12 μm , the tensile strength of lap joint specimens could reach 220 MPa (Dharmendra et al. 2011). Fig.9 shows the IMC layer of interface that the surface of steel coated with the four types of flux powder. The thickness of IMC layer that specimens coated with SiO_2 flux powder is the thinnest and the average thickness of IMC layer is approximately 6.45 μm , as shown in Fig.9c. On the contrary, the average thickness of IMC layer that specimens coated with ZnO flux powder is the thickest and the average thickness of IMC layer is approximately 14.62 μm , as shown in Fig.9d. Qin et al. (2017) demonstrated that Zn is avoided to be directly heated by arc and the evaporation of Zn is decreased. Liquid filler Al alloy can spread on the surface well because the co-existence of Zn and activating flux powder. The flux and retained Zn facilitate the spread of filler metal on steel, which greatly improves its spreadability. However, different proportions of KAlF_4 and K_3AlF_6 are applied to display different spreadability of Al alloy on steel surface, which may produce different temperature between Al alloy and steel surface. Due to the highest process temperature area influenced by the arc heating, it could be affected by the arc leading to a thicker IMCs layer. In this study, the surface of galvanized steel sheet coating with CaF_2 , TiO_2 and SiO_2 flux powder, the thicknesses of IMC layer are less than 10 μm . Due to the highest process temperature on the surface of base metal, the IMC layer of FZ presents a saw tooth shape, which may be influenced by the arc heating, as shown in Fig.9d. The results showed that the specimens produced by coating with ZnO flux powder may increase the temperature on the surface of galvanized steel sheet. It decreases the tensile strength of the Al/steel butt-joint specimens in this study.

Fig. 9 Effect of flux powder on weld-brazing interface.

4. Conclusions

During the MIG weld-brazing process for the Al/steel butt-joint specimens, four types of activating flux powder were selected to coat on the surface of galvanized steel sheet. The specific results are summarized as follow.

- (1) The activating flux powder were coated with 0.3 mm thickness on the surface of galvanized steel sheet that increasing the heat input excessively, results in the appearances of weld bead are incomplete and numerous spatters. In order to obtain higher quality of butt-joint welds, the thickness of activating flux should be accurately control at 0.1 mm thickness.
- (2) The CaF_2 flux powder was applied as a suitable flux which the spreadability of filler material on galvanized steel sheet surface become better. When SiO_2 flux powder was coated, the grains of FZ were coarser than other activating fluxes. However, the surface of galvanized steel sheets coated with SiO_2 flux powder, the butt-joint specimen has the highest tensile strength. The average tensile strength of dissimilar materials butt-joint specimens is 160.6 MPa.
- (3) When the CaF_2 or SiO_2 flux powder was coated, the higher heat inputs cause efficient escape of Zn-vapor from the

molten bead deposit, which decreases the amount of porosity in the FZ. It improves the tensile strength of the Al/steel butt-joint specimens.

- (4) When the CaF_2 , TiO_2 or SiO_2 flux powder was coated, the thicknesses of IMC layer were less than 10 μm . However, the specimens produced by coating with ZnO flux powder may increase the temperature of FZ, the thickness of IMC layer was about 14.62 μm and the IMC layer presents a saw tooth shape.

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