Investigating Novel Hybrid Joining Techniques

Kaiyu Li, Fengyun Zhang
Northeastern University, Shanghai, China

***Abstract*—**Joining of 1mm thick aluminium 6061 to titanium TC4 was conducted using Bypass-current MIG welding-brazed, and stable welding process and good bead appearance were obtained. The Joint profile and microstructure of Ti/Al joints were observed by optical microscopy and SEM and then the structure of the interfacial reaction layers were analysed in details. It was found that the intermetallic compound layer at the interfacial top is in the form of columnar crystal, which is in short and dense state. A mount of AlTi were observed at the interfacial layer near the Ti base metal while intermetallic compound like Al_3Ti, $TiSi_3$ were formed near the Al base metal, and the $Al_{11}Ti_5$ transition phase was found in the centre of the interface layer due to the uneven distribution inside the weld pool during the welding process. Tensile test results show that the average tensile strength of joints is up to 182.6 MPa, which reaches about 97.6% of aluminium base metal. Fracture is prone to occur in the base metal with a certain amount of necking.

***Keywords*—**Bypass-current MIG welding-brazed, Al alloy, Ti alloy, joint characteristics, mechanical properties.

I. INTRODUCTION

DISSIMILAR metal composite structures have the advantages of low cost, lightweight and high performance [1]. Specially, the Al/Ti composite structure is widely used in the aerospace industry because of its superior performance [2]. However, it is still a great challenge to join aluminium and titanium due to the great differences in physical properties between them. This is because that large amount of brittle intermetallic compounds will occur during the Al/Ti joining process, reducing the mechanical properties of the joints. Although a valid connection of aluminium and titanium could be realized by laser-arc hybrid welding [3], arc welding-brazing [4] and friction stir welding [5], but these methods need to use the vacuum environment or other key equipment.

The bypass-current MIG welding-brazing (BC-MIG) technology is suitable for joining aluminium and titanium due to its merits of low heat input, stable arc and droplet transferring process and low cost [6], [7]. This process applied the bypass arc to form a coupling arc with the main MIG arc and to divert some current from the main arc, which changed the distribution of stress field and heat input of the droplet and the weld pool. In this way, the weld defects could be avoided with the good seam formation ensured. In this paper, experiments were conducted on 6061 aluminium alloy and TC4 titanium alloy plates. The metallographic microscope, scanning electron microscope and energy spectrum analyser, and the tensile testing machine were applied to study the organization and the mechanical performance of the joints. Besides, the effects of the bypass current on the organizational characteristics of the joint interface were analysed. The research will provide a deep understanding and basic theoretical data of the welding process using the bypass-current MIG arc welding-brazing method for Al/Ti dissimilar metals.

II. EXPERIMENTAL MATERIALS AND METHOD

A. Experimental Materials

The specimens used for this study were 6061 aluminium alloy and TC4 titanium alloy with the dimension of 200mm×50mm×1mm. The chemical compositions of the alloys are listed in Tables I, II. The filler material used was 4043 aluminium alloy wire of 1.2 mm in diameter and the results were also shown in Table I.

TABLE I
CHEMICAL COMPOSITIONS OF 6061 ALUMINUM ALLOY AND FILLER METAL

Alloys	Si	Fe	Mg	Al
6061	0.4-0.8	0.7	0.8-1.2	Bal.
Filler metal	4.5-6.0	0.8	0.05	Bal.

TABLE II
CHEMICAL COMPOSITIONS OF TC4 TITANIUM ALLOY

Fe	Si	O	V	Al	Ti
≤0.30	0.15	≤0.20	3.5-4.5	5.5-6.8	Bal.

B. Method

Fig. 1 displays the principle of bypass-current MIG welding-brazing method. It can be seen that the total welding current I can be decoupled using a non-consumable tungsten electrode into base metal current Im and bypass current Ip. The base metal current Im can be kept at a desired level by adjusting bypass current Ip, while the current of melting filler wire is kept at a high level. Thus, the BC-MIG process can help the reliable joining of magnesium alloy to steel. The main welding parameters are listed in Table III.

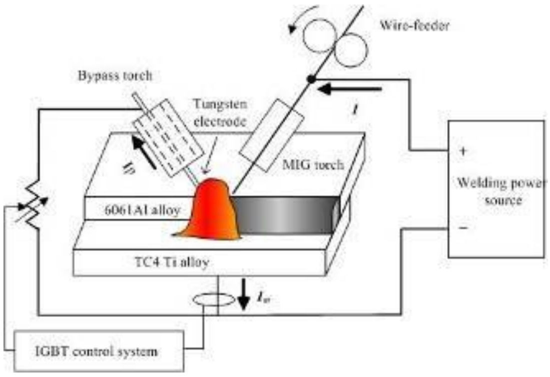


Fig. 1 Schematic drawing of BC-MIG processing

TABLE III

WELDING PARAMETERS USED FOR THE STUDY

Welding parameters	Details
Main current	56A
Main arc voltage	15.4V
Flow rate of argon in the MIG torch	15L/min
Bypass current	40A
Flow rate of argon in the bypass TIG torch	5L/min
Welding speed	13.1mm/s
Distance between filler wire and bypass tungsten	3.5mm
Distance from the MIG torch to the workpiece	12mm
Distance from the bypass electrode to the workpiece	2mm
Angle between the bypass electrode and the filler wire	45°

III. RESULTS AND DISCUSSIONS

A. Weld Appearance and Microstructure

The seam appearance of the bypass-current MIG arc welding-brazed Al/Ti joint is shown in Fig. 2. As can be seen, the seam was smooth and uniform without obvious welding defects. In the experiment, the aluminum plate was placed on top of the titanium base material, making the aluminum closer to the arc. Besides, the arc center is located in the middle of aluminum and titanium base materials. As a result, the melting of aluminum base material increased reasonably while only a little titanium melted, which had a beneficial effect on the formation of welding-brazing layer. On the other hand, the main MIG arc got more stable with the bypass arc added and the welding spatters were decreased. Meanwhile, the coupling arc can preheat the titanium plate while melting the filler wire, which helped the molten solder wet and spread more uniform on the titanium plate. The weld seam was thus more beautiful.

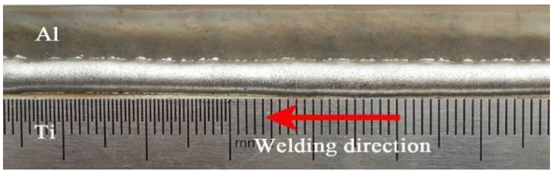
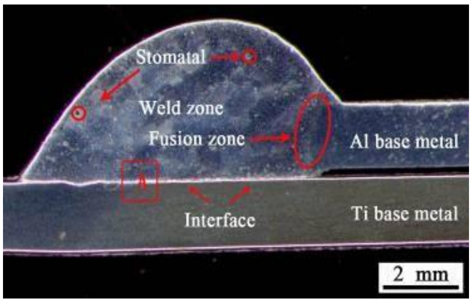
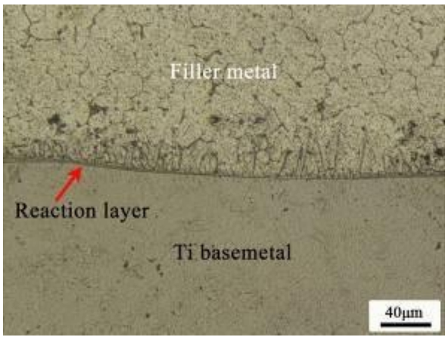


Fig. 2 Appearance of Al/Ti lap joint made by BC-MIG

Fig. 3 shows the joint morphology of the Al/Ti seam. From Fig. 3 (a), the aluminum alloy base material partial melted near the seam, mixing with the liquid solder and then forming the seam at the upper side of the lap joint. The titanium downside did not melt due to the high melting point, and the liquid aluminum alloy wetted and spread on the surface of the titanium alloy. The brazing connection was formed through the mutual dissolution diffusion effect among the elements, and the entire joint displayed a typical welding-brazing morphology. Fig. 3 (b) shows the microstructure of the zone A in Fig. 3 (a). It can be seen that the intermetallic compounds near the upper side of the interface layer existed in columnar form and the needle columnar crystal has short and dense state. In the seam zone, the elements in the interface layer melted to form the structure of eutectic network, part of which were coarse and over-burnt.



(a) Cross-section in OM of Al/Ti joint

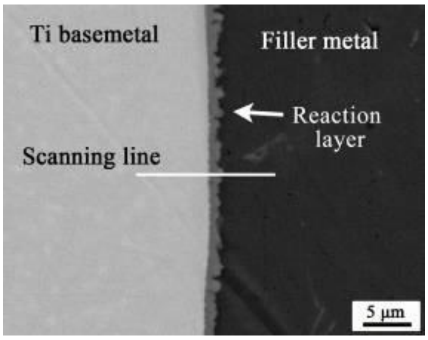


(b) Microstructure in SEMof Al/Ti joint

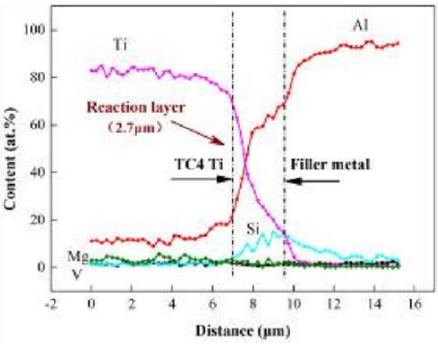
Fig. 3 Cross-section and microstructure of Al/Ti joint

B. Interface Analysis

The EDS line scan analysis was conducted to reveal the concentration fluctuation of main elements along the reaction layer between Al alloy and Ti alloy. Fig. 4 (b) shows the EDS line scanning results corresponding to the interfaces presented in Fig. 4 (a). It can be seen from Fig. 4 (b) that element Ti declined sharply in the interface, while the distribution of element Al was the opposite, and the element Si enriched in the Al alloy side of interface. The interface layer thickness consists of element Ti, Al and Si was about 3 mm. In the BC-MIG process, the crystallization of liquid filler wire was under non-equilibrium conditions, and the higher heating and lower cooling of filler wire was produced at pool, which made the different intermetallic compounds were formed in the weld owning to element diffusion with different heat inputs. Based on the Al-Ti and TI-Si binary diagram, it was therefore identified that the AlTi phases were formed on the Ti alloy side of the interface, as well as the Al_3Ti and $TiSi_2$ were supposed to be on the Al side of the reaction layer. Meanwhile, the $Al_{11}Ti_5$ transition phases were produced at interface with changing of heat input.



(a) Interfacial microstructure morphologies



(b) EDS line scan result corresponding to the interface

Fig. 4 Morphology and EDS of the interface layer

XRD analysis was performed on the interface to further identify the phases of the weld. Fig. 5 shows the XRD patterns of region surface in the reaction layer. As can be seen, Al_3Ti, $TiSi_2$ and TiAl intermetallic compounds were presented on the interface, as well as Ti, Al and Si phases. Meanwhile the transition phase was also appeared in the reaction layer through the observation of peak value in figure.

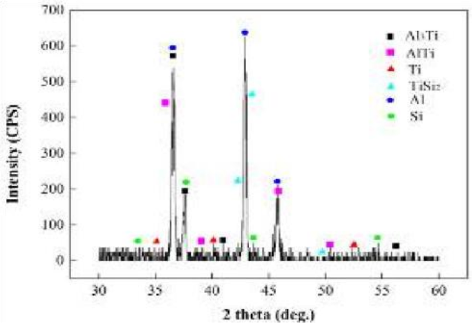


Fig. 5 XRD pattern for the reaction layer

C. Mechanical Properties

The tensile test of the specimens was carried on the Zwick/Roell Z010 testing machine at room temperature, and the tensile speed was 2mm/min. Fig. 6 shows the shear strength of the specimens. It was found that the average shear strength of the BC-MIG joint was up to 180.8MPa, about 96.6% of the strength of Al base metal (187.1MPa), and the maximum shear strength reached 182.6MPa, about 97.6% of Al base metal. Fig. 7 presents the stress-displacement curve of the Al/Ti joint. Fig. 8 displays the observation of the organization in the fracture zone. As can be seen, the fracture occurred in the affect zone of the aluminum alloy rather than the Al/Ti reaction layer, which indicated that the Al and Ti atoms at the interface region bonded tightly. It was also found that there was a necking phenomenon on fracture before crack of the joint, which indicated that the BC-MIG joint has good plasticity and high tensile strength.

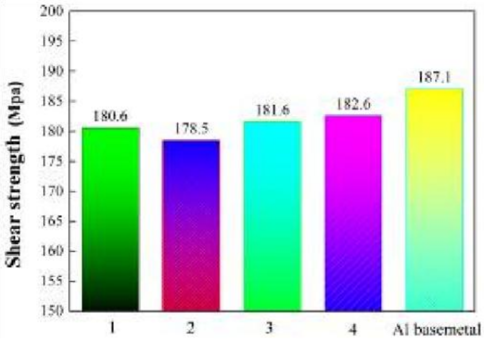


Fig. 6 Strength of different specimen joints

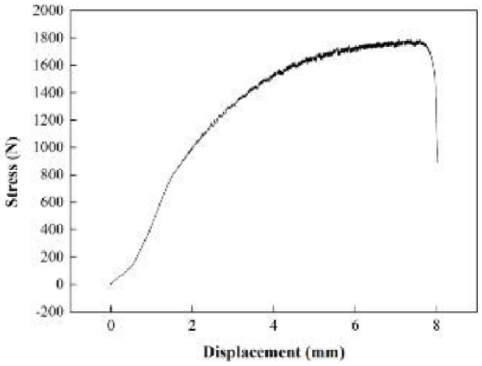


Fig. 7 Relation between tensile displacement and strength

Fig. 8 Fracture location of tensile test

IV. CONCLUSION

In this study, BC-MIG has been developed successfully for joining the dissimilar metal of 6061 aluminum alloy to TC4 titanium alloy. The following conclusions could be drawn:

1) The BC-MIG process is a stable process, which can be used to achieve the reliable joining of Al alloy to titanium alloy with a good weld appearance and high shear strength.
2) The weld was presented the typical morphology of molten brazing joint. It is found through the EDS analysis that AlTi phase is supposed to be near the side of Ti alloy, while Al_3Ti and $TiSi_2$ phase are found near the Al side. In addition, the Al11Ti5 transition phase was also appeared in the reaction layer.
3) The shear strength of the joints could reach182.6MPa, about 97.6% of Al base metal. The location of the fracture was at the heat-effect zone, and the angle between fracture line and stress direction was 45°. The fracture appearance was gray, showing the characteristics of ductility fracture.

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