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The microstructure and mechanical properties of fluxless gas tungsten arc welding–brazing joints made between titanium and aluminum alloys

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ABSTRACT

Butt joining of a titanium alloy to an aluminum alloy by gas tungsten arc welding–brazing using an Al-Si eutectic filler wire without flux is investigated. The butt joints have dual characteristics, being a welding on the aluminum side and a brazing on the titanium side. The thickness of the reaction layer varies with position in the titanium alloy interfacial area of the joint, ranging from 2 to 5 μm. At the upper part of interfacial area, the reaction layer includes only the rod-like $TiAl_3$ phase with 10 at.% dissolved Si. At the bottom of interfacial area, the reaction layer consists of the needle-like $\tau 1$ phases ($Ti_7Al_5Si_{12}$) and the block-like $TiAl_3$ phase. Hardness of the reaction layer near the welded seam/Ti alloy interface was as much as 400–500 HV. The highest tensile joint strength observed was 158 MPa. Tensile joint failure was by cracks initiating from the reaction layer at the bottom of the joint propagating into the welded seam at the upper part of the joint.

1. Introduction

Aluminum (Al) and titanium (Ti) alloys are used in industry to reduce weight and improve strength. As a result, various joining processes have been developed to bond aluminum alloys to titanium alloys. Examples are laser welding–brazing [1], friction bonding [2,3], friction stir bonding [4], diffusion bonding [5,6], brazing [7] and transient liquid phase bonding [8]. Unfortunately, Al and Ti alloys cannot be joined successfully using conventional gas tungsten arc (GTA) welding due to differences in the physical, chemical and metallurgical properties of the base metals. These differences result in the formation of large quantities of brittle intermetallic compounds that seriously degrade the mechanical properties of the joints: there is still much fundamental work to be done to find optimum process parameters. Tungsten inert gas welding–brazing of aluminum alloy–steel butt joints [9,10] has been accomplished, and this method has great potential to prevent the dissolution of steel into the weld metal so that a continuous joint can be made by the deposition of fused filler metal without the melting the base metal. For joining Ti/Al, previous studies [11] have mainly focused on laser welding–brazing with a flux-cored wire. The presence of flux improves the wetting and spreading of liquid filler metal on the Ti surface, but after welding, the residual flux deposits on the surface of base metal near the welded seam are very difficult to remove. However, without flux, the liquid filler metal will not wet or spread on the Ti surface during dynamic arc heating. To date, little has been published on fluxless Ti/Al GTA welding–brazing.

In this study, Ti/Al GTA welding–brazing joints were made successfully without any flux. The macrostructure and microstructure of the joints were analyzed and the mechanical and fracture properties were evaluated.

2. Experimental procedure

The materials used were 2024-T6 aluminum alloy and Ti–6Al–4V titanium alloy in 3 mm sheet form. The 2.5 mm diameter filler wire was 4047 Al–12Si alloy. No flux was present in the filler wire and none was added externally. The nominal chemical compositions of the base materials and filler wire are shown in Table 1.

All sheets were cut into nominal 100 × 50 mm samples, a 30° bevel was cut on one long edge of each sample, and the surface was cleaned using abrasive paper and acetone. To make the test joints, two samples were butted together, with the two beveled edges forming a groove. GTA welding–brazing was done using an AC-GTA welding source. The welding parameters were 70–150 A current, giving an arc length of 3.0–4.0 mm. The welding speed was 75 mm/min with an argon gas flow rate of 10 L/min.

After welding, a typical cross-section of the joint was cut and mounted in self-setting epoxy resin in an as-clamped condition. Then the metallographic samples were polished to a mirror-like surface aspect and etched for 10 s in a single batch using Keller's reagent. The macrostructure of the joint was investigated using optical microscopy (OM, Olympus PM-20) and the microstructure of reaction layer were measured by scanning electron microscopy

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Table 1
Chemical compositions (wt.%) of 2024 aluminum alloy, Ti–6Al–4V titanium alloy and filler wire.

Constituent	Mn	Cu	Mg	V	Fe	Ti	Si	Al	Zn
Ti–6Al–4V	–	–	–	3.60	0.30	Bal.	–	6.21	–
2024	0.80	3.90	1.40	–	0.14	0.15	0.55	Bal.	0.27
Filler wire	<0.05	<0.30	<0.10	–	<0.80	0.77	11.0–13.0	Bal.	<0.20

(SEM, FEI Quanta 200F) with energy dispersive spectrometer (EDS) used for local chemical analysis. The interfacial reactants in the joint were identified by selected area diffraction pattern (SADP) in the transmission electron microscope (TEM, FEI Tecnai F30). TEM specimens were prepared with cutting, grinding and ion milling to electron transparency. Thin sheets (8 mm × 8 mm × 0.3 mm) were cut from brazing zone where the interface reaction zone was approximately located in midline by a linear cutting machine. The thin sheets were thinned down into parallel sided and semi-thin sheets with thicknesses of around 50 μm through several steps of coarse grinding, fine grinding and mechanical polishing. The semi-thin sheets were then cut into 3 mm discs. Ion milling was performed on both sides of the specimens with two beams of 4 kV Ar ions by using a Gatan 691 Ion-Miller. After repeated attempts, the specimens with electron transparency at reaction layer have been achieved.

The microhardness of the welded specimens was determined by a Vickers hardness tester (Akashi HM-102) under a load of 200 g for 10 s dwell time ($HV_{0.2}/10$). The tests were carried out on three randomly selected points in every measurement region, and the average value was employed as the test result. Tensile strengths of the Ti/Al joints were carried out on full-width strips (15 × 98 mm) at a constant speed of 1 mm/min using an Instron 5569 tensile testing machine at room temperature. Under the condition of the same welding parameters, three specimens were fabricated for the tensile test, and then average values of the tensile strength were obtained. In order to evaluate the tensile strengths of these samples accurately and avoid the influence of the excess weld metal on joining strength, the joints were ground to be flat.

3. Results and discussion

3.1. Weld appearance

Fig. 1 shows the typical appearance of a Ti/Al GTA welding–brazing joint. It is clear that the surface of the joint is smooth, and the Ti alloy has been well wetted by the filler giving a consistent joint on both sides. No cracks were observed on the interface between the welded seam and Ti alloy, nor were undercuts or incomplete fusion observed in Al alloy side. Internal defects such as cold shuts were not observed giving an early indication the joints are sound. The test region is 60 mm long and 94 mm wide, Fig. 1b shows the specimen cutting patterns.

3.2. Macrostructure

The effects of the welding current on the joint characteristics are shown in Fig. 2. At 100 A welding current, the filler metal only spreads on Ti alloy surface, which does not melt at all, as shown in Fig. 2a. There is a narrow range of optimum welding currents of 110–120 A, in this range, the filler metal spreads fully on the Ti alloy surface to form a sound joint. The joint has the typical welding–brazing dual characteristics (see Fig. 2b). The Al alloy base metal melts and is thus a welded joint, and the molten Al mixes with the molten filler metal to form fusion area. The Ti alloy base metal does not melt and is thus a brazed joint, where wetting with the molten filler metal forms the brazing interface layer. We have observed some isolated micro-pores (<0.2 mm) or short chains of micro-pores in the welded seam close to the Al alloy side. Such pores are very common in GTA welding of Al alloy, and are caused by entrapped gaseous impurities, as shown in Fig. 2c and d. By increasing the welding current to 130 A, the upper part of the Ti alloy groove melts and cracking occurs in the welded seam nearly perpendicular to the interface after welding due to the formation of significant quantities of intermetallic compounds.

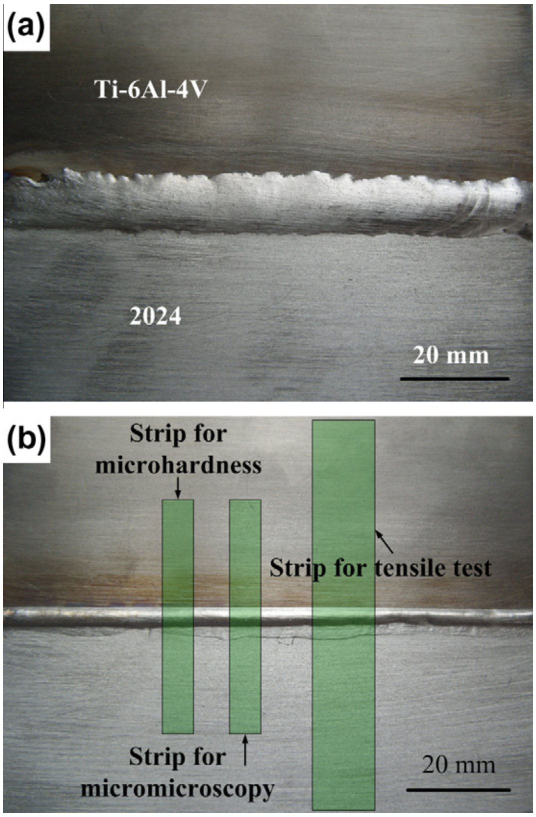

Fig. 1. Typical weld appearances of the Ti/Al GTA welding–brazing joint: (a) top and (b) underside.

3.3. Microstructure

Liquid filler metal has fully spread on the Ti alloy surface to form a good surface. The mixing of the Ti alloy and the melting filler metal is effectively avoided when GTA welding–brazing. Furthermore, the formation of the intermetallic compounds at the interface is controlled, as shown in Fig. 3a. The welded seam, as shown in Fig. 3b, has a mainly dendritic structure. The micrographs clearly show a-Al grains, granular Si and compound Mg_2Si [12]. As shown in Fig. 3c, there are four different zones: the base metal, a heat affected zone (HAZ), a fusion zone (FZ) and the welded seam. The dendritic structure in the welded seam is nearly perpendicular to the fusion line, being induced by the higher cooling rate and the direction of conductive heat flow during cooling. During the welding process, a fusion zone was formed by melting the Al alloy and