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Effect of hot dip aluminising on interfacial microstructure and mechanical properties of Ti/Al joint by TIG arc welding brazing

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The joint of Al 5A06 and aluminised Ti–6Al–4V dissimilar alloys was achieved by means of tungsten inert gas arc welding brazing. The effect of aluminized coating on the spreading behaviour of filler metal on Ti substrate was studied. The spreadability of liquid filler metal on the Ti substrate was enhanced obviously due to the presence of aluminised coating. The interfacial reaction layer was characterised by a uniform lamellar layer of $TiAl_3$ intermetallic, with a thickness of 1 μm. Sound joints with well appearance were obtained, and the optimised tensile strength of the joint reached 216 MPa. The failure initiated from the interfacial layer at the root face and then propagated within the weld seam at the upper part of the joint. Capable welding parameters were broadened by the presence of aluminised coating for dissimilar metal joining of Ti/Al.

Keywords: Ti/Al, Hot dip aluminising, Intermetallic compound, Arc welding brazing

Introduction

Titanium and its alloys with low densities, high specific strength and high corrosion resistance have been widely used in the aerospace and automobile industries.[1] The compound structures of titanium and aluminium (Ti/Al) fabricated by joining technique have a wide range of great applications due to weight reduction and low cost. However, the differences between Ti and Al are enormous, such as crystal structures, melting points, coefficients of heat conductivity and thermal expansion. Thus, the joining of Ti and Al is of great challenge, and conventional fusion welding process that generally operates at high heat input levels promotes the formation of a large amount of brittle intermetallic compounds (IMCs), which degrade joint properties. To address this issue, various attempts have been conducted, including diffusion welding,[2–4] transient liquid phase bonding,[5,6] explosive welding,[7] friction welding,[8] laser joining,[9] brazing,[10] friction stir welding[11,12] and ultrasonic assisted brazing.[13,14] Recently, cold metal transfer welding brazing joining of Ti6Al4V and Al A6061-T6 was carried out using AlSi5 wire.[15] The joints had dual characteristics of a welding joint on the aluminium side and a brazing joint on the titanium side.

Two major factors should be considered when joining Ti and Al dissimilar alloys, namely, the spreadability of Al based fillers on Ti substrate and the control of brittle intermetallics. The $TiAl_3$ brittle IMC layer was produced along the Ti/Al interface zone, resulting in a low joint strength.[2,8,16] The critical value of the thickness of the intermetallic layer was ~10 μm, and the joint tensile strength decreased seriously when its thickness exceeded the critical value.[8] Investigations on laser welding brazing indicated that non-uniform IMCs were produced along the brazing interface, and cracks propagated easily at the bottom interface of butt joints due to the heterogeneity.[17] Interfacial reaction layers of laser welding brazing joint were composed of α-Ti, nanosize granular $Ti_7Al_5Si_{12}$ and serration shaped $TiAl_3$.[9] To overcome this issue, rectangular spot and V shape grooves were developed to improve the spreadability of liquid filler and decrease the temperature gradient along the interface. Borrisutthekul *et al.* proposed to add a heat sink at the joint zone to suppress the growth of the interfacial layer in the Fe/Al joint. This practice reduced the thickness of IMC layer and increased the joint strength.[18]

Tungsten inert gas (TIG) arc welding brazing, which offered a great potential to weld dissimilar materials, was developed. It was expected to improve the heterogeneity of the interfacial reaction at the brazing interface due to the less spatial temperature gradient compared to laser welding. The TIG arc welding brazing method had been successfully used to join Ti and Al in air without flux.[19] A keyhole was produced to enhance the spreadability of liquid filler on the Ti substrate.[20] However, the heterogeneity of the interfacial reaction was still not solved effectively, and a non-uniform IMC layer was formed through the thickness direction caused by the uneven spatial energy distribution of the arc and the relatively low welding speed. Hot dip aluminising process had been used to improve the thermal oxidation resistance of titanium alloys at high temperatures.[21] Ti/Al dissimilar metals were successfully joined by means of vacuum diffusion bonding after aluminising on the

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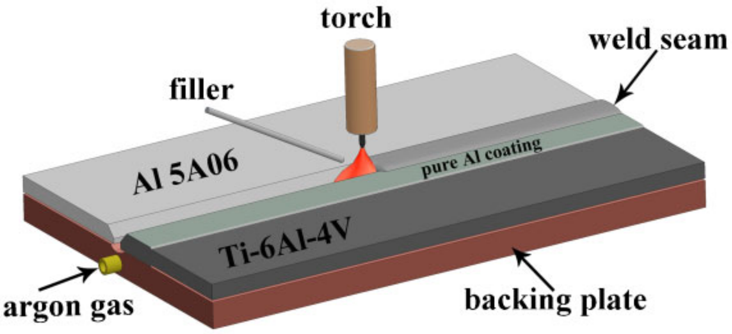


1 Schematic of TIG arc welding brazing of Ti/Al dissimilar alloys

surface of Ti sheet.[2] In addition, it was also used as a pretreating process to enhance the spreadability for ultrasonic assisted brazing.[22]

The aim of this paper is to study the influence of the aluminised coating on the spreadability of liquid filler as well as the suppression of brittle IMC layer during TIG arc welding brazing of Ti/Al dissimilar alloys. The microstructure and mechanical properties have been systemically studied.

Experimental

The base metals were Ti–6Al–4V alloy and Al 5A06 alloy plates, which were cut into 100×70×2 mm coupons. To avoid the influence of alloy element additions, pure Al filler with diameter of 2·5 mm was adopted. The chemical compositions of the plates and filler wire are listed in Table 1. A single Y groove was machined with a bevel angle of 45° and a root face of 0·5 mm along the length direction on the plates. Hot dip aluminising experiments were conducted in a medium frequency induction furnace at the temperature of 750°C. Commercial flux QJ201 was dissolved in acetone to produce a suspension, and the suspension was brushed onto the surfaces of Ti plates. The Ti plates were dipped into the molten pure Al metal bath for 1 min and then pulled out and cooled in air. The welding process was carried out using a Panasonic YC-500WX4 welding machine. Double shielding gas of argon was provided at both sides of the matrix to avoid oxidation as well as to improve the wetting and spreading behaviour. The welding current was 120 A, and the welding torch was clamped by an automotive apparatus with the speed ranging from 90 to 180 mm min^{-1}. Filler wire was fed in front of the arc, and the arc length was about 3–4 mm. The offset distance of the electrode towards the Al plate was 1 mm in order to heat the root face of the Ti plate sufficiently. A schematic figure of the welding process is shown in Fig. 1.

To assess the influence of aluminised coating on the spreadability of pure Al filler over the surface of the Ti alloy plate, comparative experiments were conducted by arc spot welding using a 200 mg pure Al filler collar placed under the electrode in accordance with GB/T 11364-2008. The spreading area was measured to evaluate the wettability and spreadability of the filler metal on Ti substrates. Cross-sections of the samples were cut and mounted in self-setting epoxy resin in as clamped condition. The microstructures of all the samples were observed by scanning electron microscopy (SEM, Hitachi S-4700) equipped with an energy dispersive X-ray spectrometer (EDS) analysis system. Phase identification was analysed by X-ray diffraction (XRD) test after removing the aluminium by grinding on SiC paper and etching in NaOH solution. Tensile strength was measured at a speed of 0·5 mm min^{-1} (Instron-5569) according to GB/T 2561-2008 (equivalent to ISO 4136:2001). Three tensile specimens were prepared, and the average value was calculated.

Results and discussion

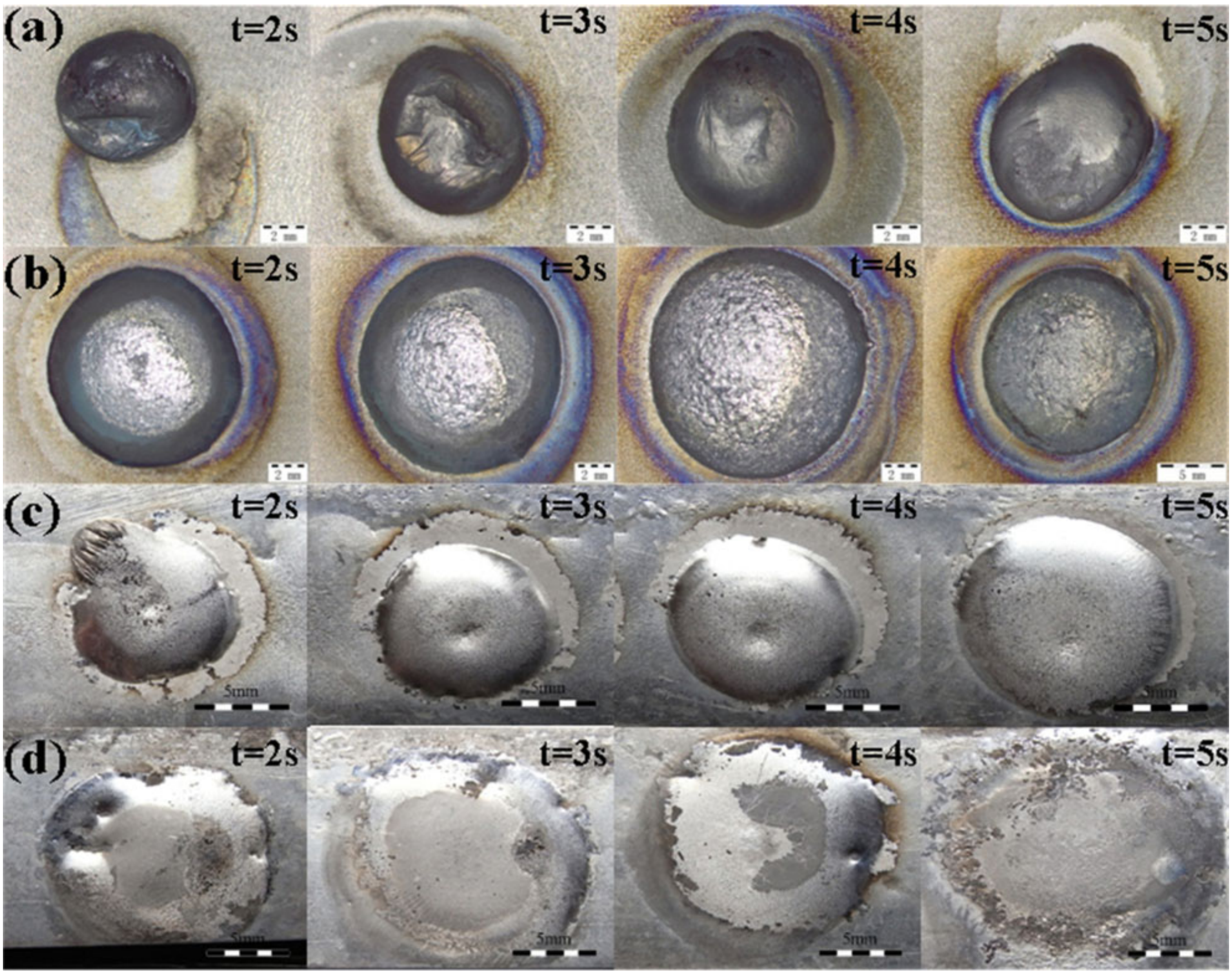
Spreading characteristics of filler on Ti substrates

The spreading characteristics of pure Al filler on the aluminised and non-aluminised Ti plates are shown in Fig. 2 under welding current of 40 and 80 A for an arc duration range of 2 to 5 s. The spreading areas of the filler increase gradually with the current and arc duration time increasing. Oxide scale can be observed obviously on the surface of the non-aluminised Ti plate due to the inferior oxidation resistance of Ti alloy at high temperatures, resulting in dark circular regions, as shown in Fig. 2*a* and *b*. However, oxide scale on the aluminised Ti surface is removed sufficiently by the cleaning action of the cathode. The glossy surfaces of the filler spreading regions can be seen in Fig. 2*c* and *d*. This could attribute to the presence of aluminised coating, which improves the thermal oxidation resistance of Ti surface at high temperatures.

The variation of spreading areas of filler metal on the Ti substrate is shown in Fig. 3. There is an increase in spreading areas with the increase of welding current and duration time. When the arc duration time ranges from 2 to 5 s, the corresponding spreading area on the non-aluminised Ti substrates varies from 30·43 to 40·34 mm^2 under 40 A current, while it varies from 79·27 up to 162·3 mm^2 under 80 A current. There is an obvious

Table 1 Chemical compositions of base metals and filler wire, wt-%

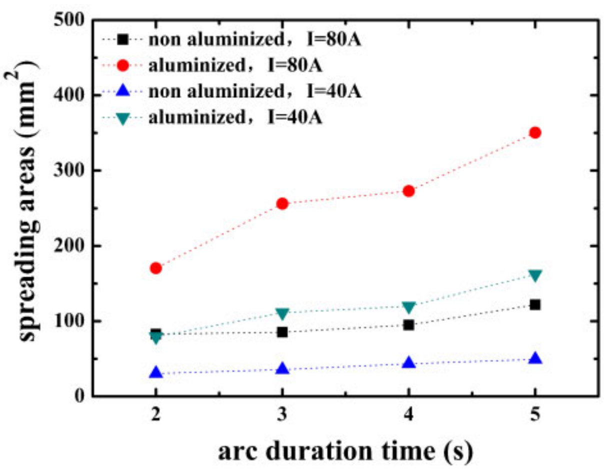
Elements	Al	Ti	Mg	Si	Cu	Mn	Fe	V
Ti–6Al–4V	5·5–6·8	Bal.	…	≤0·15	…	…	≤0·3	3·5–4·5
Al 5A06	Bal.	0·02	5·8–6·8	…	0·1	0·5–0·8	0·4	…
Filler wire	Bal.	…	…	…	≤0·1	…	…	…



a on non-aluminised Ti surface, *I*=40 A; *b* on non-aluminised Ti surface, *I*=80 A; *c* on aluminised Ti surface, *I*=40 A; *d* on aluminised Ti surface, *I*=80 A

2 Spreading results of filler after TIG arc heating

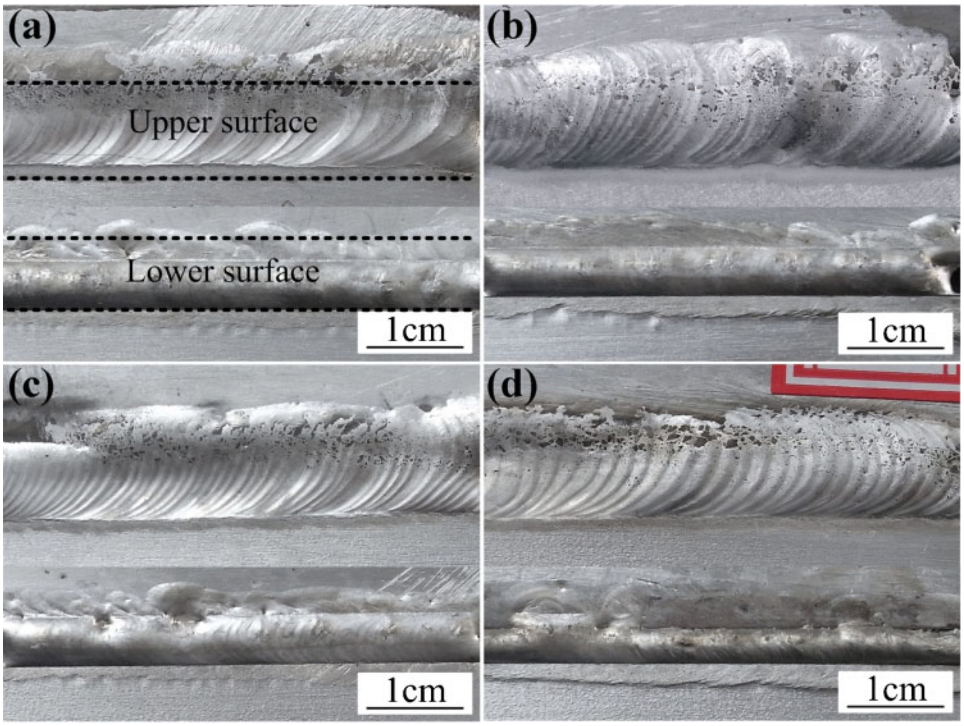
increase in the spreading areas on the aluminised Ti substrates. When the arc duration time ranges from 2 to 5 s, it varies from 82·87 to 121·91 mm^2 under 40 A current, and it varies from 170·5 up to 340·44 mm^2 under 80 A current respectively, which reaches two times that on the non-aluminised ones under the same condition. This is due to the enormous differences



3 Variations of spreading areas as function of arc duration time

between Ti and Al in crystal structures and physical and chemical properties, which result in poor wetting and spreading of Al on Ti plate. However, the physical and chemical properties between filler metal and the aluminised coating are nearly the same. Under rapid heating, cleaning action and powerful electromagnetic stirring effect of the arc, the spreading ability of the filler on the aluminised Ti surface can be facilitated remarkably. On the other hand, for surface aluminising, the coating acted as a barrier and avoided the Ti substrate from oxidation. Oxide film on the aluminised coating surface is easily removed by the cleaning action of the cathode during arc heating.

The weld appearance of the resultant Ti/Al joints by arc welding brazing is shown in Fig. 4. With welding speed ranging from 90 to 150 mm min^{-1}, all joints have good formation without any cracks, undercuts or incomplete fusion. When the welding speed increases to 180 mm min^{-1}, the joint still has a sound front appearance but a little incomplete wetting on the back surface due to the insufficient flow of molten filler. It needs enough time for the arc to heat the root face of Ti plate; otherwise, the wetting and spreading of the filler on the back of Ti plate would be hindered. A relatively low welding velocity should be adopted. However, the spreadability of the filler on the aluminised Ti surface is vastly enhanced. The molten filler could spread easily on



a I=120 A, v=90 mm min^{-1}; *b* I=120 A, v=120 mm min^{-1}; *c* I=120 A, v=150 mm min^{-1}; *d* I=120 A, v=180 mm min^{-1}

4 Weld appearance of both faces

both faces of the Ti sheet facilitated by the arc forces, and a relatively high welding velocity can be achieved. Consequently, single face welding double faces forming Ti/Al joints are easily achieved. The capable welding brazing parameters are broadened due to the presence of the aluminised coating. Furthermore, a relatively high welding velocity results in a decrease in the heat input, which would be favourable for controlling the interfacial reaction and suppressing the formation of brittle IMCs.

Microstructure of interfacial reaction layer

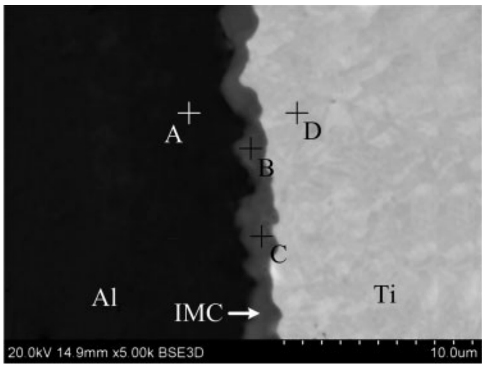
The microstructure at the interface between Ti substrate and the coating is characterised by a grey lamellar IMC layer with a thickness of 0·5 to 1 μm, as illustrated in Fig. 5. The EDS results (seen in Table 2) indicate that the stoichiometry ratio of Ti atom to Al atom is nearly 1 : 3 at the interfacial layer (point B and C), implying that the IMC phase is $TiAl_3$. Chemical reaction occurs between solid Ti and liquid Al during hot dip aluminising process, and consequently, the formation of lamellar $TiAl_3$ intermetallic indicates that metallurgical bond has been achieved. $TiAl_3$ intermetallic is a preferential product during the reaction between solid Ti and liquid Al, which forms before other binary IMCs, namely TiAl, Ti_3Al, $TiAl_2$ and Ti_2Al_5.[3,23,24] $TiAl_3$ phase is detected from the XRD patterns, as shown in Fig. 6, which is consistent with the EDS analysis results.

Table 2 Energy dispersive X-ray spectrometer results at interface of Ti substrate and aluminised coating, at-%

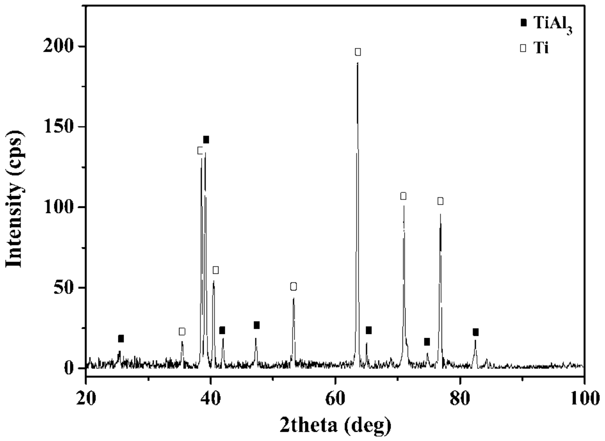
Location	Ti	Al
A	6·17	93·83
B	24·17	75·83
C	20·15	79·85
D	88·24	11·76

Figure 7 presents the typical cross-sectional view of Ti/Al butt joints. No apparent melting on the Ti side is found, while the aluminium alloy side exhibits a typical fusion joint with the molten filler, as shown in Fig. 7*b*. The variation of contact angle of the aluminium welded beads on the surfaces of non-aluminised and aluminised Ti plates is not obvious. However, the liquid filler spreads for a longer distance on both the front and back faces of Ti plate (indicated in elliptic dotted line) in the aluminised Ti/Al joint compared with the non-aluminised Ti/Al joint. This can be attributed to the improvement of the spreadability of the filler on the aluminised Ti substrate.

The TIG arc exhibits a high temperature gradient through the thickness. Thermal cycle at the interface differs from the top to the bottom, inducing an uneven distribution of reaction layer morphologies. Figure 8 displays detailed interfacial microstructure images of the rectangular zones labelled A to D in Fig. 7*b*, corresponding to the upper part, intermediate part, bottom of the groove and root face zone respectively. The interfacial microstructures exhibit a serrated and rod shaped



5 Image (SEM) at interface of Ti substrate and aluminised coating



6 **X-ray diffraction patterns of IMC layer at interface of Ti base metal and aluminised coating**

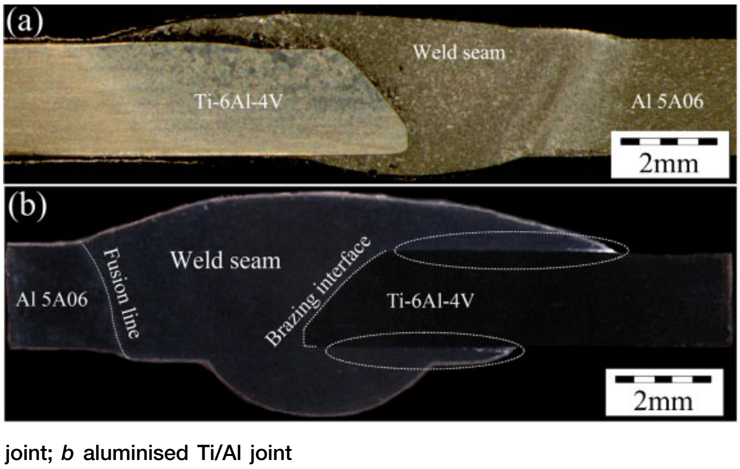
morphology with a thickness of 3 to 8 μm in a, b and c, and a loosely continuous morphology in d with a thickness of 5 μm. These morphologies are observed from the interfaces of the non-aluminised Ti/Al butt joints, and the welding parameters are current of 120 A with brazing velocity of 90 mm min^{-1}. However, the joint presents a more uniform lamellar structure with 1 μm thickness along the whole brazing interface of the aluminised Ti substrate under the same welding parameters, as shown in Fig. 8*e–h*. The thickness of the interfacial reaction layer decreases slightly as the brazing velocity increases to 180 mm min^{-1}, as shown in Fig. 8*i–l*. The thickness of the interfacial layer of the aluminised Ti/Al joints decreases obviously compared to that of the non-aluminised sheet joints.

The temperature of the Ti alloy base metal at the interface quickly increases to >1273 K under rapid heating of the arc.[19] The molten filler metal wets and spreads along the hot surface of Ti substrate due to arc pressure. With no aluminised coating, the Ti atoms dissolve into the liquid Al filler bath directly and forms a solution of Al(Ti), and then the Al atoms diffuse into the solid Ti substrate and a forms solid solution of Ti(Al) during arc heating. This leads to solid–liquid interaction and accelerates the diffusion rate of Ti atoms in the molten filler metal. Consequently, the diffusion of a large amount of Ti atoms into liquid filler induces the formation of $TiAl_3$ phase on the Ti alloy side during solidification. Moreover, high heat input promotes the thick IMC layer with an uneven distribution through thickness direction due to non-uniform arc heating. Whereas the interfacial layer formed during hot dip aluminising process can act as a diffusion barrier and decreases the diffusion rate of Ti atoms into the molten filler metal. Thus, the amount of diffused Ti atoms in the liquid filler metal reduces, and only a small amount of $TiAl_3$ can nucleate and grow during the subsequent solidification process. Furthermore, low heat input and high brazing velocity resulted from the improvement of the spreadability, are also advantages to reduce the process temperature and thereby reduce the growth of intermetallic layer. Based on the Ti–Al binary phase diagrams shown in Fig. 9, the melting point of $TiAl_3$ (~1320°C) is much higher than that of Al (~650°C). Thus, the $TiAl_3$ will keep solid condition during the welding brazing process. The formation of excessive brittle $TiAl_3$ intermetallic is suppressed, and a uniform lamellar interfacial structure with thickness of 1 μm is obtained, which benefits the mechanical properties.

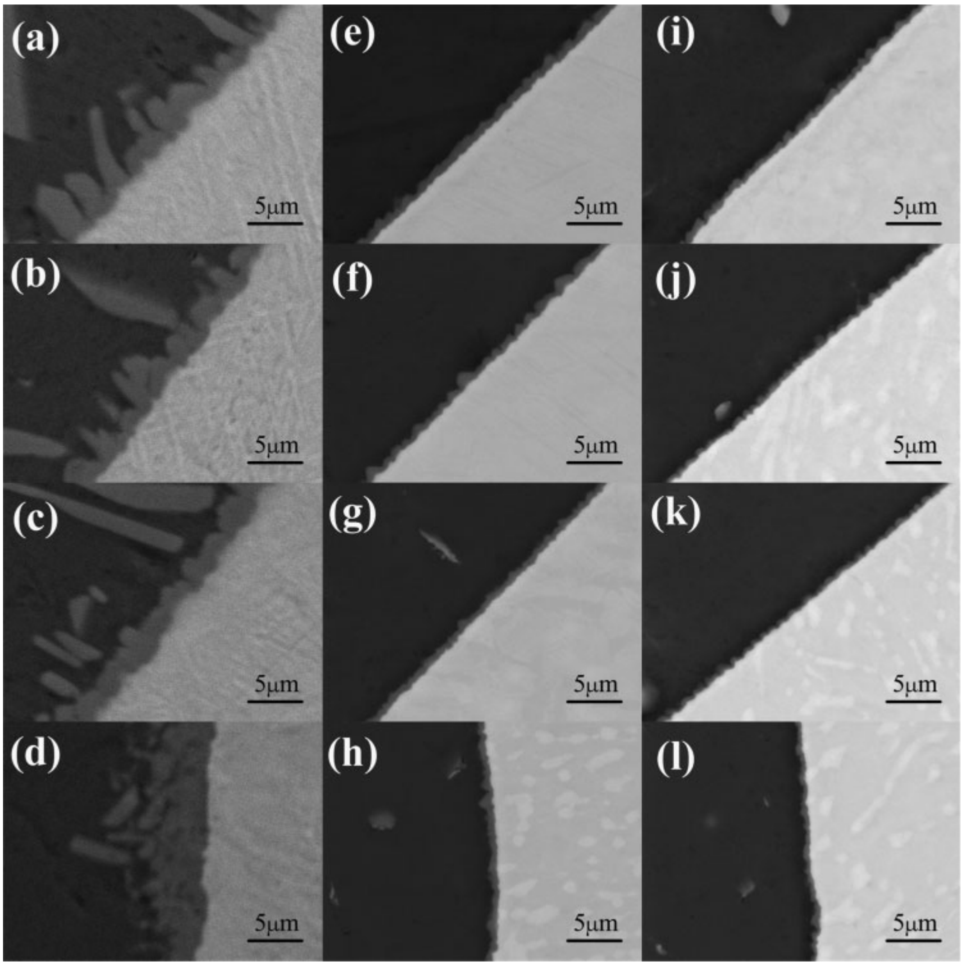
To confirm the distribution of elements Ti and Al at the brazing interface, EDS line analyses were carried out, as shown in Fig. 10. As seen, from the Ti base metal to the weld metal, the content of the Al element increases gradually, while the content of Ti decreases as a whole. However, it is found that the distribution ratio of Ti/Al keeps stable basically at the zone of the lamellar shaped layer in the weld metal, which identifies that they are IMCs. Phase identification of the interfacial structure of welding brazing joints is carried out by XRD after removing Al by grinding and deep etching. $TiAl_3$ and Ti are detected, as seen in Fig. 11. The interfacial layer remains the same phase structure, implying that only growth behaviour of the IMC layer proceeded without any new phase nucleating during the welding process.

Tensile strength and fracture

All joints are ground flat to avoid the influence of the excess weld metal for tensile tests. The average tensile strength of the non-aluminised Ti/Al joints is 117·5 MPa, and the maximum value reaches 139 MPa; however, the average tensile strength of the aluminised Ti/Al joints is 204·5 MPa, and the maximum value reaches 216 MPa. This can be attributed to the effective control of the formation of excessive brittle intermetallics. Figure 12 displays the corresponding paths of the cracks in the fractured joints. The non-aluminised Ti/Al joints failed



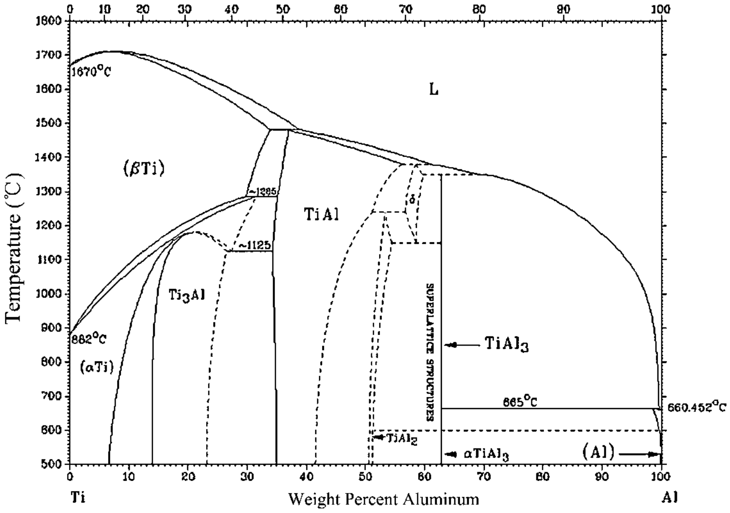
a non-aluminised Ti/Al joint; *b* aluminised Ti/Al joint
7 **Macroscopic cross-sections of non-aluminised and aluminised Ti/Al TIG arc welding brazing joints**



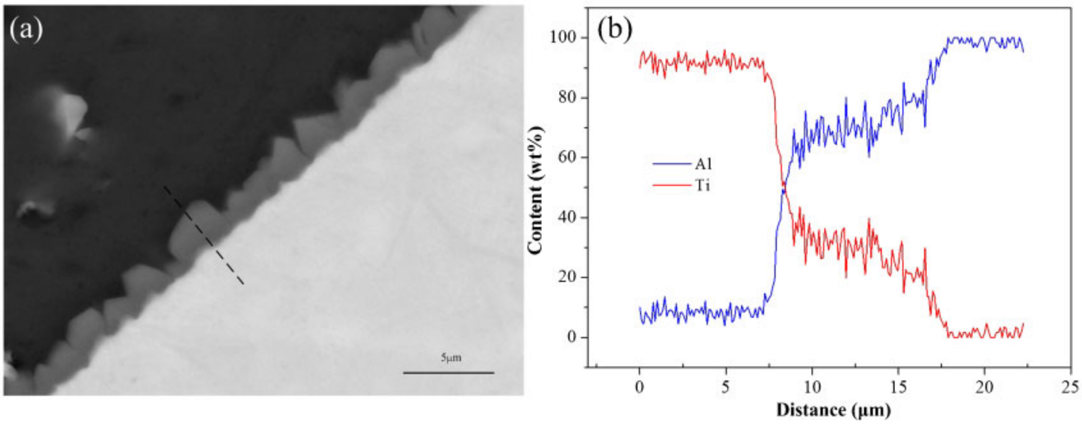
a–d interfaces of non-aluminised Ti/Al joints; *e–l* interfaces of aluminised Ti/Al joints

8 Micrographs of regions taken from corresponding areas labelled as rectangles A–D in Fig. 7*b*

entirely at the IMCs layer/Ti interface, as shown in Fig. 12*a* and *c*. The fracture initiates from the interfacial reaction layer at the root face and extends through the $TiAl_3$ layer/Ti interface owing to the poor bonding at the IMCs layer/Ti substrate interface and stress concentration caused by the brittle IMC layer. The $TiAl_3$ phase, with a tetragonal DO_{22} structure, is characterised by extreme brittleness and easily becomes an internal source of microcracks during loading.[19] However, after hot dip aluminising, the thickness of the IMC layer decreases obviously, which has a significant influence on the joint properties. As shown in Fig. 12*b* and *d*, the fracture initiates from the interfacial layer at the root face, where stress concentration is maximal due to the root geometry. The crack tends to propagate in the weld seam at the upper part, implying that the bonding strength at the

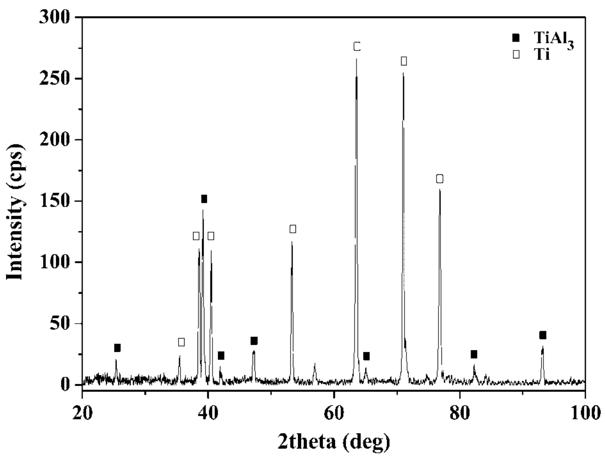


9 Ti–Al binary phase diagram



a interface of aluminised Ti/Al joints; *b* result of line scanning analysis

10 Line scanning results (EDS) at interfaces

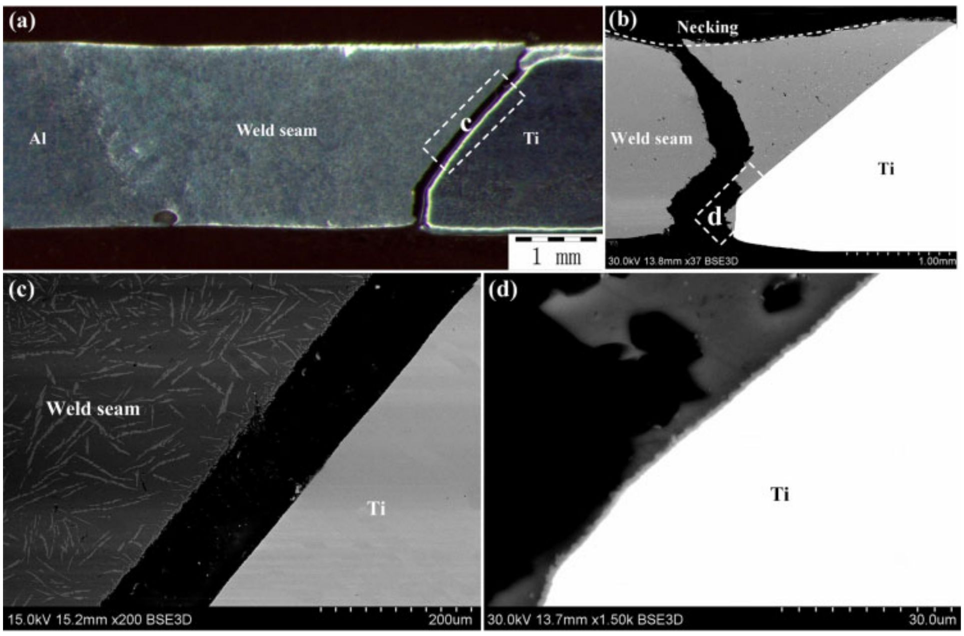


11 X-ray diffraction spectrum of interfacial reaction layer of aluminised Ti/Al arc welding brazed joints

IMCs layer/Ti base metal interface and the IMCs layer/weld seam interface is higher than that of the weld seam. The weld seam displays an obvious necking behaviour, which shows that the joint undergoes a large plastic deformation. The interfacial layer with lamella morphology can prevent crack propagation. If the cracks propagate in the lamellar reaction layer, plastic deformation will occur in the Ti substrate and Al weld seam near the crack tip due to the thin reaction layer, which will in turn lead to the rapid increase in deformation energy. Thus, sound joints are achieved with uniform lamellar interfacial reaction layer morphology.

Conclusions

A different metal joint of Ti–6Al–4V and Al 5A06 is successfully achieved by TIG arc welding brazing with the assistance of hot dip aluminising preprocessing. The spreadability of the liquid filler metal on the aluminised Ti sheet surface is enhanced obviously. The capable welding parameters are broadened, and single face welding double



a non-aluminised Ti/Al joints; *b* aluminised Ti/Al joints; *c* higher magnification of zone c in *a*; *d* higher magnification of zone d in *b*

12 Fracture of joints welded at 120 A

face forming is easily achieved. With the presence of the aluminised coating, direct interdiffusion of atoms is hindered, and the thickness of the interfacial reaction layer decreases obviously. A uniform lamellar $TiAl_3$ interfacial reaction layer with thickness of $\sim$1 μm is formed along the brazing interface. The tensile strength of the aluminised Ti/Al arc welding brazed joints is up to 216 MPa. Firm bonding has been achieved at both the IMC layer/Ti base metal and the IMC layer/weld seam interfaces of the aluminised Ti/Al joints.

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