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Research on cracking initiation and propagation near Ti/Al interface during TIG welding of titanium to aluminium

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Abstract

Titanium alloy TA15 and aluminium alloy Al2024 were welded by tungsten inert-gas arc welding using AlSi12 filler wire. Microstructure and phase constituents of weld zone near Ti/Al interface were analyzed by means of scanning electron microscopy and X-ray diffraction. Initiation and propagation of welding cracks near Ti/Al interface were investigated. Supplementary measures on controlling of cracking were clarified. Titanium and aluminium alloys were partially fusion welded in the upper part while brazed in the middle and bottom parts of the joint. In Ti/Al fusion zone, intermetallics Ti_3Al + Ti_5Si_3, TiAl + Ti_5Si_3 and $TiAl_3$ formed as three layers orderly from titanium side to weld metal. Near Ti/Al brazed interface, intermetallics Ti_5Si_3 and $TiAl_3$ formed as two layers from titanium side to weld metal. Two kinds of cracks appeared near Ti/Al interface. One kind initiated in weld zone with high residual stress; the other initiated in brittle Ti-Al intermetallics. Preference propagation paths of cracks are along the interfaces between different intermetallic layers or cross micro-defects near Ti/Al interface.

K e y w o r d s: titanium, aluminium, fusion welding, brazing, welding crack

1. Introduction

Due to the demand for reduction of fuel consumption, titanium and aluminium lightweight constructions are widely applied in aerospace and automobile industries. Ti/Al hybrid structures have advantages in comparison to single material for both strength and lightweight requirements [1]. It is important to produce sound Ti/Al joints without defects. Titanium and aluminium have low inter-solubility and Ti-Al brittle intermetallics (IMCs) form easily during thermal welding. Welding cracks initiate easily in Ti-Al IMCs, which would seriously degrade properties of the Ti/Al joint. To obtain good combination of titanium with aluminium, studies were conducted using technologies such as tungsten inert-gas arc (TIG) welding [2, 3], laser welding [4, 5] and friction stir welding (FSW) [6, 7]. By adopting a novel welding-brazing technology, thickness of Ti-Al IMC layers near Ti/Al interface has been controlled to a low level. However, IMC layers in the joint still have relatively high crack sensitivity, and most of the joints were fractured at Ti/Al interface during tensile test [8]. Thus it is important to study the initiation and propagate mechanism of welding cracks during thermal welding. Laser welding-brazing of titanium to aluminium alloys was investigated in reference [9], influences of interfacial reaction layer morphologies on initiation and propagation of cracks were studied. However, few researches focusing on initiation mechanism and propagation paths of welding cracks during TIG welding have been published in literature.

In the present research, TIG welding of titanium to aluminium dissimilar alloys was investigated using AlSi12 filler wire. Microstructure and phase constituents of weld zone near Ti/Al interface were studied. Initiation and propagation mechanism of welding cracks were analyzed. The work aims to provide analysis of crack sensitivity of interfacial reaction layers. Supplementary measures are clarified to control cracking during TIG welding.

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

Elements	Ti	Al	Si	V	Mg	Mo	Zr	Fe	Cu	Zn	Mn
TA15	bal.	6.5	0.10	1.8	–	1.0	2.0	0.10	–	–	–
Al2024	–	bal.	0.5	–	1.5	–	–	0.5	4.5	0.3	–
AlSi12	0.15	bal.	12.0	–	0.1	–	–	0.8	0.3	0.2	0.15

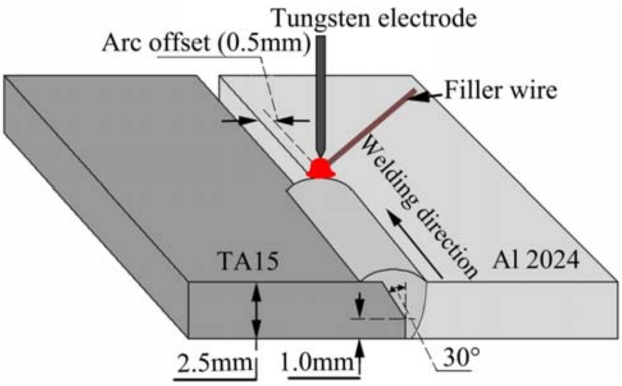

Fig. 1. Schematic drawing of TIG welding.

2. Experimental procedure

Titanium alloy TA15 and aluminium alloy Al2024 rolled plates with dimensions of 200 mm × 50 mm × 2.5 mm were used as base metals. Element Si has been demonstrated to be highly effective in suppressing growth of Ti-Al IMCs [10], so the AlSi12 wire with diameter of ø 2.0 mm was chosen as filler metal. Chemical compositions of base metals and filler metal are listed in Table 1. Both TA15 and Al2024 are active light metals, and all the plates need to be strictly cleaned up before welding. Surfaces of TA15 plates were cleaned in acidic solution (HNO_3 20 vol.%, HF 2 vol.%, H_2O 78 vol.%). Surfaces of Al2024 plates were cleaned in alkali liquor (NaOH 8 vol.%, H_2O 92 vol.%). Oxidation films in surface of base metals were removed by grinding process. At last, all the plates were cleaned using an ultrasonic cleaner, washed in alcoholic solution and then dried.

To improve the spreadability of liquid filler metal, the joint was arranged in the pattern of "Y" with narrow gap, and the bevel angle was 30° in titanium side. The TIG welding was carried out using WES-250P TIG welding source. Diameter of tungsten electrode was ø 2.4 mm. The welding parameters were: welding current of 100–110 A, arc voltage of 11–12 V, welding rate of 0.15 m min^{-1}. The filler wire was fed by hand. Welding process was carried out in a device full of argon shield gas. Geometrical parameters of joint and welding torch position are shown in Fig. 1. In order to reduce fusion of titanium and suppress formation of Ti-Al IMCs, the offset of tungsten electrode towards aluminium base metal was 0.5 mm.

After welding, typical cross-sections of the joints perpendicular to the welding direction were ground and polished to a mirror-like finish. Then the samples were etched with chemical etchants (HF 15 vol.%, HNO_3 15 vol.% and H_2O 70 vol.%) for 5 to 10 s. Microstructure characteristics of weld zone near Ti/Al interface were observed using optical microscopy (OM) and HITACHI SU-70 field emission scanning electron microscopy (FE-SEM). Chemical compositions near the interface were tested using HORIBA EX-250 energy-dispersive X-ray spectroscopy (EDS). Phase constituents near Ti/Al interface were analyzed using X-ray diffraction (XRD) with an analysis angle ranging from 20° to 100°.

3. Results and discussion

3.1. Microstructure of weld zone near Ti/Al interface

Typical cross-section of the joint is shown in Fig. 2a. During TIG welding, Al2024 base metal was melted and mixed with liquid AlSi12 filler metal. Consequently, a fusion zone was formed at Al side. Owing to offset of tungsten electrode towards Al2024, only part of TA15 surface was melted. Thus the solid titanium interacted with liquid mixed metal to form a complex interface. Liquid mixed metal had spread fully on the titanium alloy surface to form a good joining.

Microstructures of weld zone near Ti/Al interface at different locations that are marked as A–D zones in Fig. 2a are shown in Figs. 2b–e. Because TIG welding process has high temperature gradient in the thickness direction, weld thermal cycle suffered at Ti/Al interface from top to bottom of the joint was different [9]. Eventually a visible unequal-thickness reaction zone formed adjacent to Ti/Al interface. According to Figs. 2b,c, owing to direct heating by welding arc, titanium surface was partially melted and mixed with liquid mixed metal in zones A and B. Thick continuous reaction layers were formed due to reactions between Ti, Al and Si. Because Ti-Al IMCs have intrinsic brittleness, cracks could initiate easily with low welding stress. Thus formation of too much continuous IMCs would degrade properties of the joint for having a high crack sensitive [11]. In the C zone, peak temperature suffered

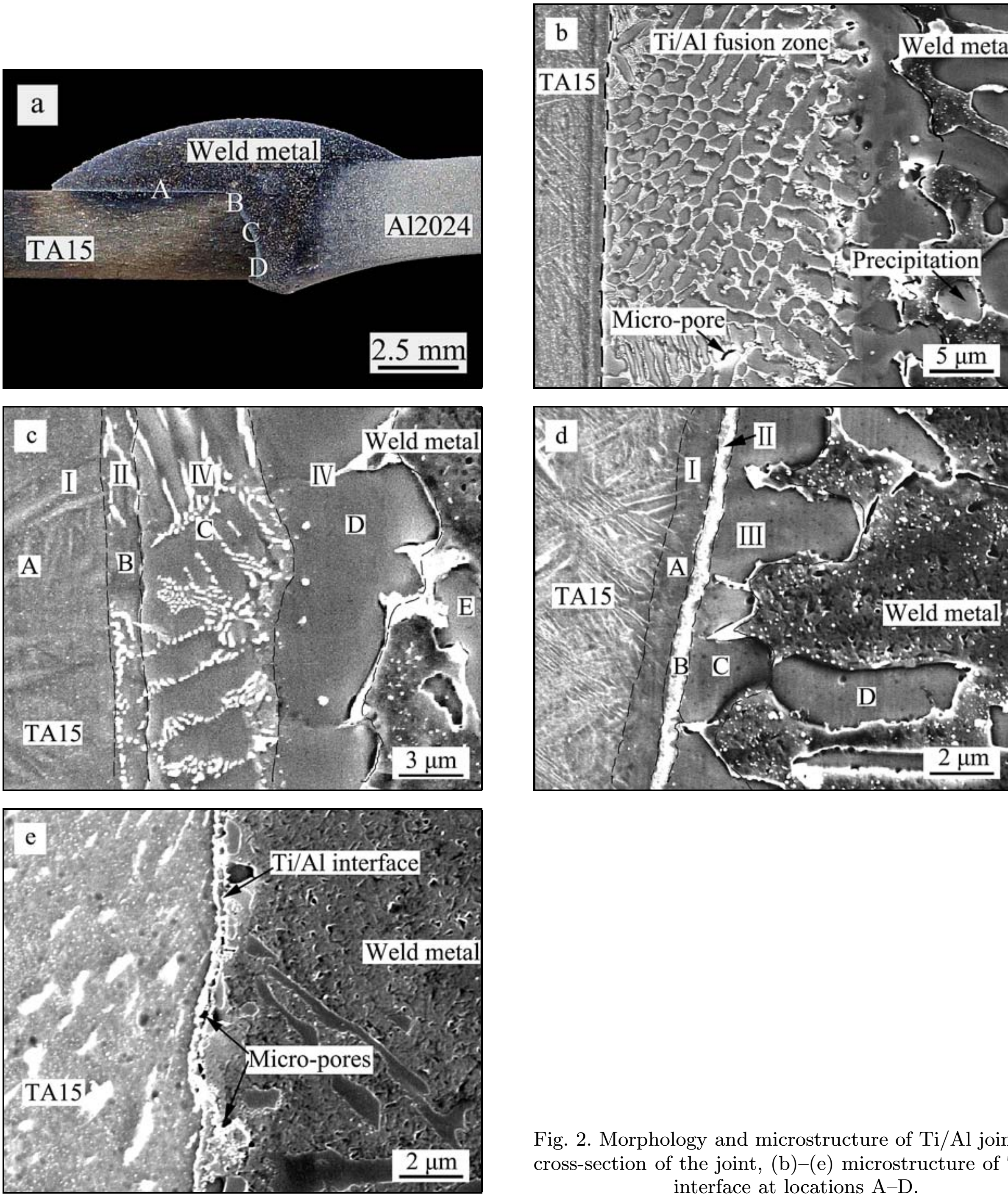

Fig. 2. Morphology and microstructure of Ti/Al joint: (a) cross-section of the joint, (b)–(e) microstructure of Ti/Al interface at locations A–D.

at Ti/Al interface was not so high, and TA15 was not melted. A thin serrate reaction layer was formed owing to interactions between titanium with liquid mixed metal, as shown in Fig. 2d. In the bottom zone D, owing to insufficient reactions between titanium and liquid mixed metal, no obvious reaction layers were observed. According to Fig. 2e, micro-pores are easily observed near the Ti/Al interface, and combination of titanium with weld metal is weak.

3.2. Phase constituents of reaction layers

The joint was broken apart from the Ti/Al interface, and phase constituents in both sides were analyzed using XRD. The test results in Ti side and in Al side are shown in Figs. 3a,b. Under the TIG welding condition, IMCs Ti_3Al, TiAl, $TiAl_3$ and Ti_5Si_3 were observed near the Ti/Al interface.

Distribution order of IMCs in reaction layers near Ti/Al interface was determined using EDS. SEM mi-

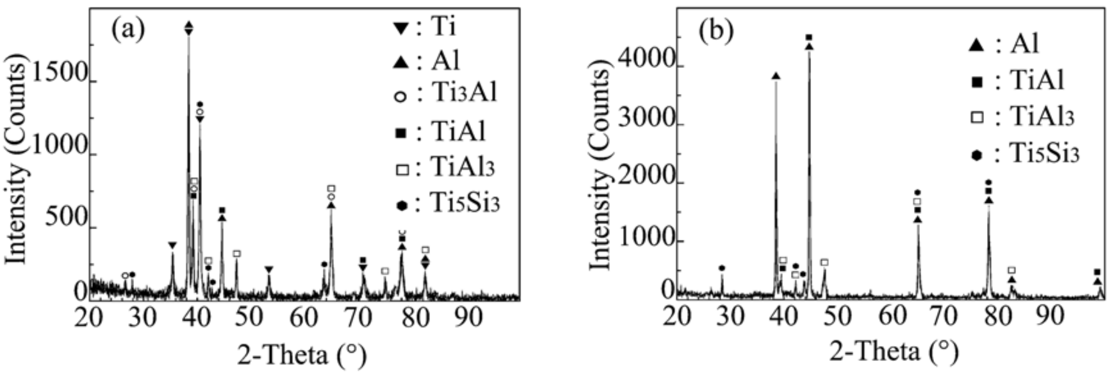

Fig. 3. X-ray diffraction profiles of the Ti/Al interface: (a) Ti side, (b) Al side.

Table 2. EDS element analysis at locations A–E in fusion zone (at.%)

Elements	Ti	Al	Si	V
A	84.46	12.83	–	2.71
B	68.45	28.29	0.90	2.36
C	41.34	47.10	9.77	1.79
D	23.46	65.57	10.97	–
E	25.20	63.68	11.12	–

Table 3. EDS element analysis at locations A–D in brazed interface (at.%)

Elements	Ti	Al	Si	V
A	82.93	13.08	0.10	3.89
B	23.71	60.08	14.55	1.66
C	25.51	63.08	11.05	0.36
D	25.31	63.96	10.73	–

crograph of Ti/Al fusion zone is shown in Fig. 2c. The fusion zone consists of four layers marked as I, II, III and IV from titanium side to weld metal. Chemical compositions of selected locations marked as A, B, C, D and E in Fig. 2c were analyzed using EDS and the test results are listed in Table 2. In location A, atomic percents of Ti and Al are 84.46 at.% and 12.83 at.%, respectively. The results suggest that the layer I is α-Ti solution. In location B, atomic ratio of Ti to Al is about 3 : 1. So the layer II is composed of IMC Ti_3Al. Atomic percent of Ti in location C is equal to Al, thus the layer III is composed of IMC TiAl. In location D, atomic ratio of Ti to Al is about 1 : 3. Thus the layer IV is composed of IMC $TiAl_3$. A few nano-particles are distributed in layer II and layer III. According to observations of XRD, the nano-particles may be the IMC Ti_5Si_3. Thus the layer II is an eutectic mixture of Ti_3Al with Ti_5Si_3. The layer III is composed of TiAl + Ti_5Si_3 eutectic structure.

SEM micrograph of Ti/Al brazed interface is shown in Fig. 2d. The interface consists of three layers that are marked as I, II and III from titanium side to weld metal. Selected locations marked as A, B, C and D in Fig. 2d were analyzed using EDS and the test results are listed in Table 3. Atomic percents of Ti and Al in location A are 82.93 at.% and 13.08 at.%, respectively. The layer I is α-Ti solution. Atomic ratio of Ti to Al in location B is about 1 : 3, and the atomic percent of Si is much higher than that in other locations. According to the results of XRD analysis, the flocculent layer II is the mixture of IMCs Ti_5Si_3 with $TiAl_3$. Atomic ratio of Ti to Al in location C is about 1 : 3. Apparently, the serrate reaction layer III is mainly composed of IMC $TiAl_3$. Precipitations in weld metal were analyzed using EDS, and they were proved to be IMC $TiAl_3$, as shown in locations E in Fig. 2c and D in Fig. 2d.

3.3. Initiation of welding cracks

Morphologies of welding cracks near Ti/Al interface were observed using SEM. Welding cracks mainly initiated in three zones marked as A, B and C in Fig. 4a.

Owing to direct heating from welding arc, titanium alloy in A zone was partially melted. Thick reaction layers were formed in Ti/Al fusion zone. Ti-Al IMCs have intrinsic brittleness, and plastic deformation ability of IMCs is low [12]. Nucleation of polygonization cracks is easy in Ti/Al fusion zone [13], as shown in Fig. 4b. During solidification process, large solidification shrinkage occurred due to high thermal expansion of weld metal. Besides, large weld reinforcement resulted in high welding residual stress in the fusion zone. Thus cold cracking initiated when solidification shrinkage of weld metal surpassed the deformability of Ti-Al IMCs, as shown in Fig. 4c.

In bottom part of the joint B zone, peak temperature that Ti/Al interface suffered was relatively low. Inter-reaction of titanium with liquid mixed metal was insufficient for having a short contact reaction time. Combination of titanium with aluminium is weak, and micro-pores are easily observed near the interface, as

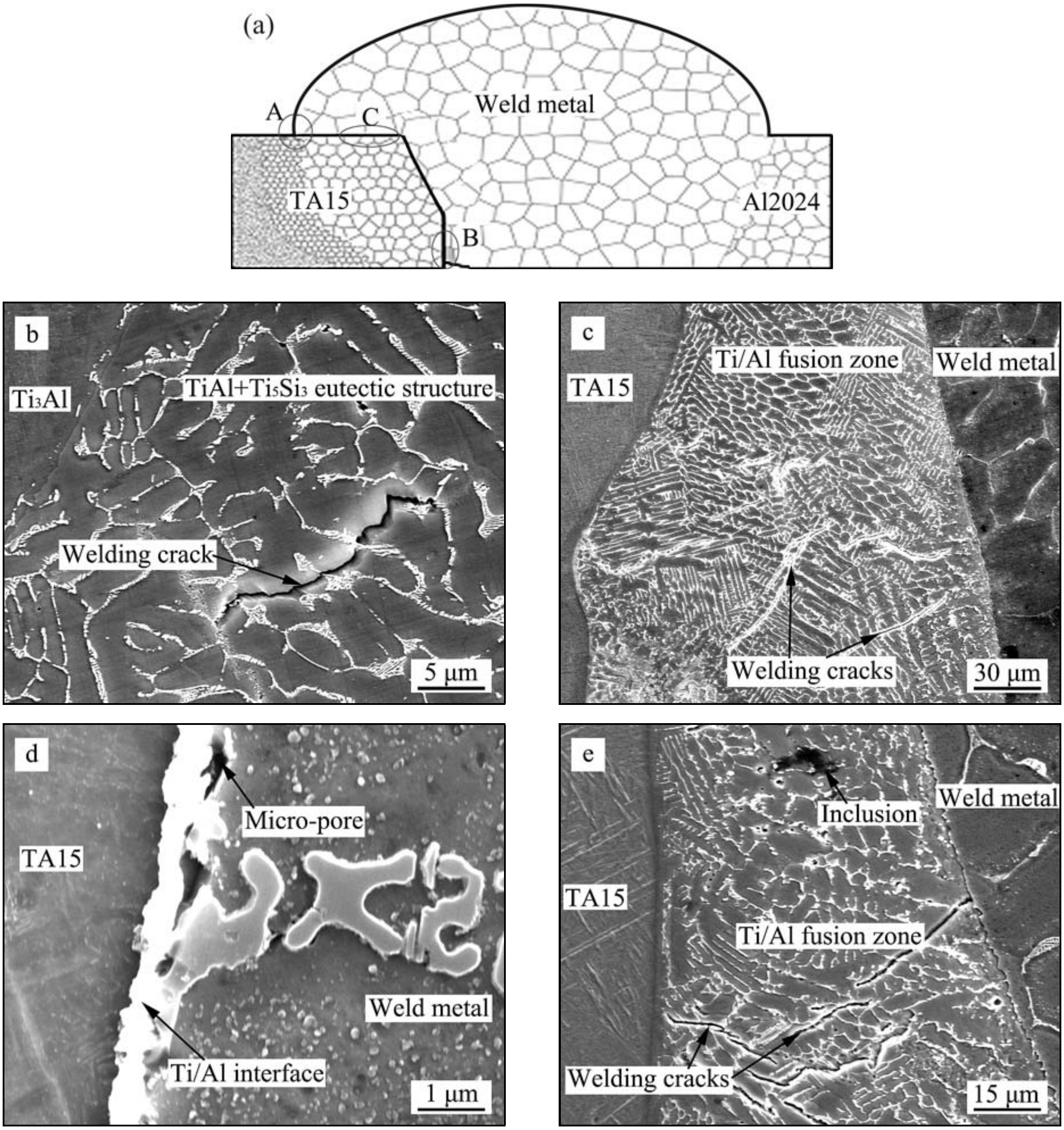

Fig. 4. Initiation of cracks near Ti/Al interface: (a) schematic diagram of Ti/Al joint, (b) crack in Ti-Al IMCs, (c)–(e) microstructure of Ti/Al interfaces at locations A–C.

shown in Fig. 4d. During the cooling process, stress concentration near pores was high and migration of dislocations occurred, which resulted in high dislocation density near the pores. Owing to different solidification conditions through thickness direction, solidification shrinkage of weld metal was uneven along the Ti/Al interface. High welding residual stress existed near Ti/Al interface in B zone. Owing to high welding residual stress, cold cracks initiated easily from the pores.

On the top surface of titanium C zone, titanium was partially melted and thick reaction layers formed adjacent to Ti/Al interface. The reaction layers are composed of brittle Ti-Al IMCs. Thus the fusion zone has high crack sensitivities, and polygonal cracks were easily formed in the IMC layers. Besides, oxide film forms easily on titanium surface during TIG welding. Oxide films were brought into molten pool by the flowing liquid mixed metal. At last, oxide films were formed into inclusions in IMC layers, as shown in Fig. 4e. The existence of inclusions resulted in high dislocation density. Micro-cracks initiated easily near these inclusions.

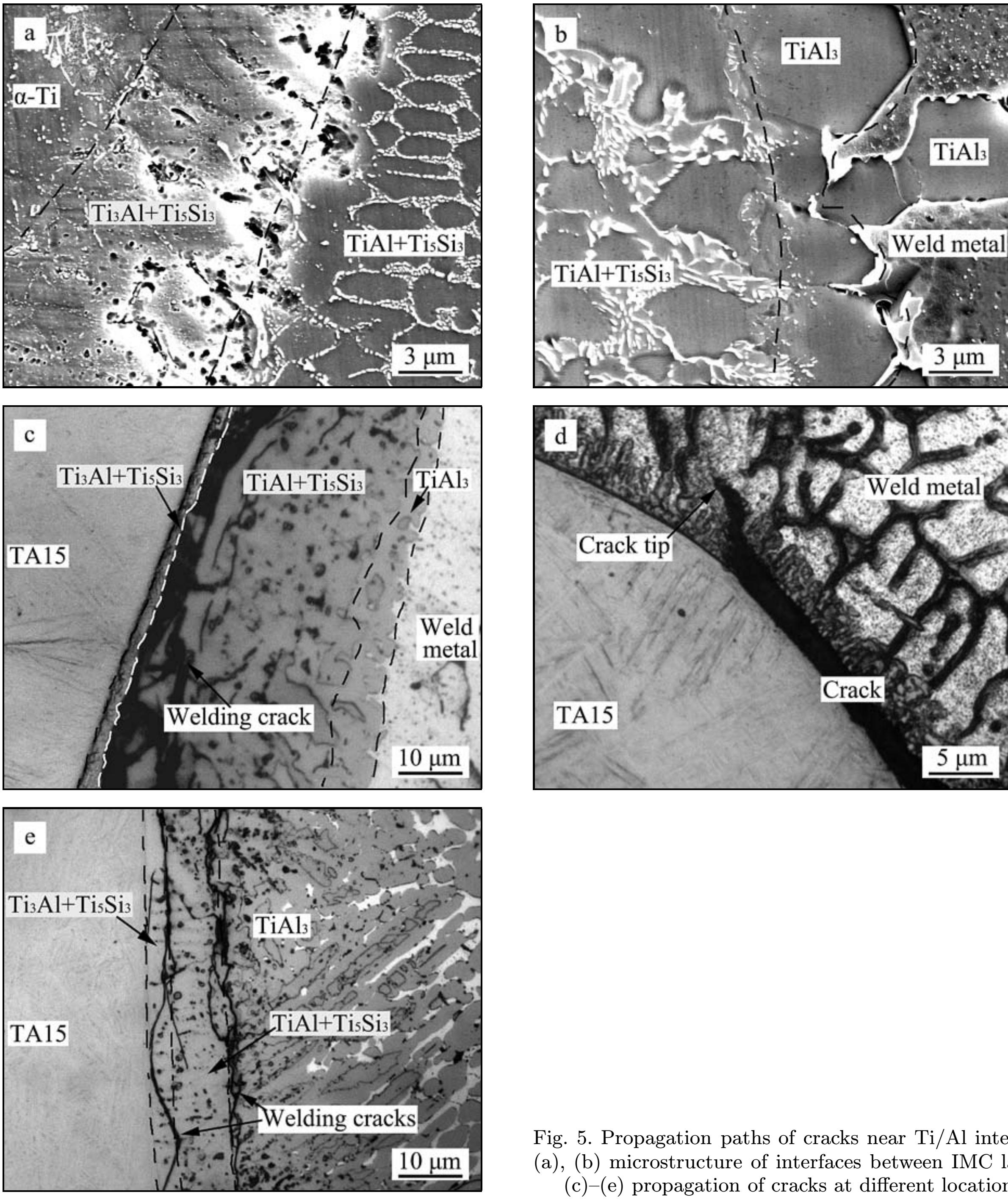

Fig. 5. Propagation paths of cracks near Ti/Al interface: (a), (b) microstructure of interfaces between IMC layers, (c)–(e) propagation of cracks at different locations.

3.4. Propagation of welding cracks

Thick IMC layers were formed in A zone, as shown in Fig. 4a. And the IMC layers take a multilayered morphology. Owing to different physical performance, IMCs had different solidification processes. In addition, coefficient of linear expansion and lattice structure of different IMCs were different. These factors resulted in high edge dislocation density near interfaces of different IMC layers. Owing to welding residual stress, dislocations migrated and accumulated to the interface between different IMC layers, and large amount of cracking sources were formed along the interface, as shown in Figs. 5a,b. Once welding cracks initiated in the fusion zone, propagation tendency of welding cracks was along the interface with high dislocations density. In A zone, welding cracks mainly propagated along the interface between Ti_3Al + Ti_5Si_3 layer and TiAl + Ti_5Si_3 layer, as shown in Fig. 5c.

In B zone in Fig. 4a, combination of titanium with weld metal was weak. Lots of micro-pores were formed in the interface, as shown in Fig. 4c. Combined area of titanium with weld metal was small due to formation of too many micro-pores. High dislocation density existed near the micro-pores, which was beneficial to the initiation and propagation of welding cracks. As shown in Fig. 5d, welding crack mainly propagated along interface between α-Ti layer and $TiAl_3$ layer. At last, welding crack was arrested in weld metal with good plasticity.

Thick Ti-Al IMC layers were formed near Ti/Al interface in C zone, as shown in Fig. 4a. Interfaces between IMC layers are weak regions in the fusion zone. Thus welding cracks mainly propagated along interfaces between $Ti_3Al + Ti_5Si_3$ and $TiAl + Ti_5Si_3$ layers or between $TiAl + Ti_5Si_3$ and $TiAl_3$ layers, which is shown in Fig. 5e.

As the formation of thick Ti-Al brittle IMCs would degrade properties of the joint [14], it is important to avoid melting too much titanium by controlling the welding heat input in a low degree during thermal welding. As most welding cracks propagate along interfaces between different IMC layers, another possible way to suppress cracking is to change morphologies of IMCs near Ti/Al interface. If IMCs form into discrete precipitations in weld metal, welding stress would be offset by plastic deformation of α-Al surrounding IMCs, and crack sensitivity of the joint would be decreased. Furthermore, microstructure difference of Ti/Al interfaces along thickness direction of the joint should be mitigated by improving distribution of welding heat input along the Ti/Al interface.

4. Conclusions

1. Titanium alloy TA15 and aluminium alloy Al2024 were butt joined using tungsten inert-gas arc welding. Titanium and aluminium alloys were partially fusion welded in the upper part while brazed in middle and bottom parts of the joint. Intermetallics $Ti_3Al + Ti_5Si_3$, $TiAl + Ti_5Si_3$, $TiAl_3$ were formed as three layers in Ti/Al fusion zone. Intermetallics Ti_5Si_3 and $TiAl_3$ were formed as two layers adjacent to the Ti/Al brazed interface.

2. Two kinds of welding cracks were observed in weld zone near Ti/Al interface. One kind initiated in weld zone with high welding residual stress, the other initiated in brittle Ti-Al intermetallics.

3. Preferred propagation paths of welding cracks were along the interfaces of different intermetallic layers or cross interfacial micro-defects with high dislocation density.

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