Mechanical properties and microstructure analysis of welding-brazing of Al/Ti butt joint with Zn foil additive

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Keywords: welding, titanium, aluminium, microstructures, mechanical properties

Abstract
TIG welding-brazing features of 5052 Al alloy and Ti6Al4V alloy in butt configuration with Zn foil additive were studied with varying welding heat input. The joint morphology, mechanical performance, microstructure and joining mechanism were investigated in terms of experiment observation and analysis. Results reveal that the TIG welding-brazing process was successfully developed to join 5052 Al alloy and Ti6Al4V alloy. With low heat input, a mass of residual Zn and a thin TiAl3 IMCs layer occurred in the fusion area and brazing area respectively. And with optimal heat input, both the homogeneous diffusion of Zn atoms and the formation of clubbed interfacial reaction layer were beneficial to enhance joint performance. The optimized Al/Ti joint with the maximum joining strength of 192MPa was obtained under the current of 90A. Fracture occurred in the weld seam zone adjacent to the interface of Al/Ti and the fracture morphology was characterized by typical dimples and tearing ridges.

1. Introduction
The dissimilar joining of Al alloy and Ti alloy has apparent potential application in motor vehicle, aeronautics and astronautics industries, which could enhance strength, high-temperature performance and corrosion resistance (attributed to Ti alloy) and reduce expenses and weight (attributed to Al alloy) [1–4]. However, the joining of Al/Ti alloys remains a challenging technical task owing to the significant mismatch in metallurgical compatibility and chemical affinity, and inevitable formation of brittle intermetallic compounds (IMCs) [5, 6]. Besides, the poor wettability between Al alloy and Ti alloy is also a problem that cannot be ignored, which seriously affects the forming of Al/Ti welded joint [7, 8]. It is worth noting that a series of approaches including laser beam welding [9, 10], friction stir welding [11–13], diffusion welding [14, 15], brazing [16, 17], explosive welding [18, 19] and ultrasonic spot welding [20–22] have been attempted to join Al/Ti dissimilar alloys, which are limited by specific operational environment and joint configuration.

Recently, welding-brazing technology has been employed to carry out the joining of dissimilar alloys, attributed to the excellent controllability of heat input and IMCs formation [23, 24]. Previous Literature has demonstrated that the welding-brazing technology has great advantages in the joining of heterogeneous metals with large melting point differences, for instance, Al/steel joint [25], Mg/Ti joint [26] and Mg/steel joint [27]. During the welding-brazing process, the welded joint shows dual welding characteristics. Partial base metal and filler metal with low melting point are melted under the thermal action of electric arc and mixed with each other, resulted in the welding joint. Whereas base metal with high melting point remains solid and reacts with molten metal to form brazing joint. Xue et al [25] investigated the wettability, interface micromorphology and joining strength of Al/steel joint obtained by welding-brazing process. The results show that Fe4Al13 phase occurred and reduced the stress concentration of interfacial reaction layer. The joining strength of Al/steel joint was enhanced to 200 MPa, which was about 70% of the tensile strength of 6061-T6 Al alloy base metal. Tan et al [26] reported the welding-brazing features of AZ31 Mg alloy to Ti6Al4V alloy in butt configuration with Ni coating. Results reveal that Mg–Al–Ni intermetallic compounds occurred in the fusion zone, and Ti3Al, Ti3Ni phase formed in...
the brazing zone. The maximum tensile strength of Ti/Mg weldment was 3.9 kN and joint failed at Mg alloy base metal. Zhao et al\[27\] studied the effect of welding heat input on the interfacial reaction layer and mechanical properties of Mg/steel joint using laser welding-brazing technology. Experimental results show that, the interfacial reaction layer evolved from AlNi phase into AlNi(α-Mg + Mg2Ni) eutectic phase. With laser power of 2kW and welding speed of 0.5 m min\(^{-1}\), the sound Mg/steel joint with fracture strength of 230 N mm\(^{-1}\) was obtained owing to the Ni coating, representing an 85% joint efficiency relative to Mg alloy parent plate.

The above literatures reveal that welding-brazing technology could improve the adaptability and flexibility of dissimilar metals joining, and provide proper heat input and restrict the formation of intermetallic compounds, which offers great potential for Al/Ti heterogeneous metals joining. Nevertheless, the previous studies were focused on the control of IMCs composition and thickness of interfacial reaction layer by altering the wire components. Of particular note is the wettability and spread of liquid Al alloy on Ti alloy surface are poor during welding-brazing process. As a result, in the present study, a Zn foil was added to improve the joint figuration and welding quality during TIG welding-brazing process.

2. Experimental procedure

2.1. Materials

5052 Al alloy and Ti-6Al-4V alloy were selected as parent materials, which were both machined to the dimensions of 60 mm × 60 mm × 1.5 mm. An Al alloy wire (Al–Si12) with 1.2 mm in diameter was used as filler material. And a 30-μm-thick Zn foil was added as an interlayer between Ti plate and Mg plate. The main chemical compositions of parent metals, filler metal and interlayer are shown in table 1.

### Table 1. The chemical compositions of parent materials, filler metal and interlayer.

| Elements (wt%) | Al | Zn | Mn | Si | V | Ti | Mg |
|---------------|----|----|----|----|---|----|----|
| 5052 Bal.     | 0.1| 0.1| 0.25| —  | — | 2.2| 2.8|
| Ti6Al4V       | 5.9| —  | —  | —  | 4.2| Bal.| —  |
| Filler metal  | Bal.| 0.15| 12.0| —  | 0.15| 0.1| —  |
| Zn foil      | —  | Bal.| —  | —  | — | —  | —  |

The schematic of TIG welding-brazing of Ti–6Al–4V plate and 5052 Al plate in butt configuration.

2.2. TIG welding-brazing process

Prior to welding, the surface of parent materials, filler metal and interlayer were polished with sandpaper in order to remove the oxide layer, subsequently cleaned with absolute alcohol and dried by cool air. The welding experiment of Al/Ti alloys was conducted by a TIG welding machine. As illustrated in figure 1, the Al alloy plate and Ti alloy plate were fixed in butt joint configuration with Zn foil in the middle location. To avoid the melting of Ti alloy with high melting point, the electrode center was skewed to the side of Al alloy plate with an offset value of 0.5 mm. Ar was applied as protective gas to protect the molten metal form oxidation. Table 2 lists the detailed welding parameters employed in this paper.

2.3. Result analysis method

After the welding experiment, the Al/Ti weldments were cut across the transverse section of the weld area for microstructure observation and mechanical performance testing. The cross sectional microstructures and
compositions of joint were characterized by the scanning electron microscope (SEM) equipped with energy dispersive x-ray spectrometer (EDS) and backscattered electron (BSE). The micro hardness of cross section was measured by a Vickers with 10 s dwell time and 200g test load. Considering the great differences in mechanical properties between Al/Ti base metal and possible effective joining strength, only the maximum joining strength of Al–Ti joint was tested at room temperature with a speed of 2 mm min\(^{-1}\). Figure 2 presents the schematic diagram of tensile testing sample. In order to improve the reliability of mechanical property data, the average tensile strength of joint obtained under each welding parameter was calculated from at least five samples.

### Table 2. The process variables adopted in the present study.

| Welding parameters | Value       |
|--------------------|-------------|
| Welding current (A) | 70–100      |
| Welding speed (m min\(^{-1}\)) | 0.2         |
| Wire feed speed (m min\(^{-1}\)) | 0.55        |
| Flow rate of shielding gas Ar (l min\(^{-1}\)) | 10          |
| Welding arc length (mm) | 2           |

Figure 2. The schematic diagram of tensile testing sample of Al/Ti joint.

Figure 3. The typical surface appearances of Al/Ti joints obtained with 70A and 100A.

3. Results and discussion

3.1. Macrostructure of Al/Ti joint

Figure 3 shows the typical surface appearances of Al/Ti joints obtained with 70A and 100A. It can be found that a narrow weld seam was formed in the Al/Ti joint. And the width of weld seam increased with the increase of welding current. Figure 4 presents the cross sectional macrostructures of weld zone of Al/Ti joints obtained with assistance of Zn foil and various welding parameters. It is worth noting that all Al/Ti joints showed excellent formation without any cracks or pores, which indicating that the interlayer of Zn foil enhanced the wettability of molten metal on the surface of Ti alloy. Dual welding features were presented in figure 4. Filler metal and Al alloy plate were melted under the irradiating of electrode arc, and the mixed liquid metal subsequently cooled to room temperature and resulted in the formation of fusion area. On the other hand, molten metal interacted with solid Ti alloy plate with high temperature to form the brazing area. The differences in microstructure between fusion
area and brazing area would be analyzed in the following chapters. Besides, figure 4 indicates that welding parameters has a significant effect on joint characteristics. As shown in figure 4(a), with current of 70A, the weld zone of joint was narrow (4.8 mm) and high (3.2 mm), owing to insufficient heat input. As the current increases, sufficient heat input thinned and broadened the weld zone, as presented in figures 4(b)–(d). It is obvious that the evolution of joint morphology is accompanied by the change of microstructure characteristics, which will affect the mechanical properties of joint.

3.2. Microstructure of fusion area of Al/Ti joint

The influences of heat input on the micromorphology of fusion area of Al/Ti joint are illustrated in figure 5. As presented in figure 5(a), a large amount of Zn elements was not sufficiently diffused into the fusion area, but segregated in the grain boundaries near the brazing area. Considering the lack of heat input (with current of 70A), the TIG arc heat could only melt part of the parent metal and had no ability to heat the molten pool metal to a sufficiently high temperature, thus hindering the full diffusion of Zn. Similar experiment results were reported by Wang et al [28]. As the current increased to 80A, greater heat input promoted the diffusion of Zn and reduced the amount of residual Zn, as depicted in figure 5(b). Figure 5(c) show that Zn element completely dissolved in fusion area with current of 90A, considering the considerable solubility of Zn under the arc heat and stirring. However, some thin clubbed IMCs occurred in the fusion area. It is apparent that, the amount and size of clubbed IMCs increased with the current increasing to 100A, as presented in figure 5(d).

The typical concentration distributions of alloy elements of fusion area (with current of 100A) were measured and illustrated in figure 6. It can be found that a mass of Ti elements were aggregated in the clubbed intermetallic compounds, indicating the formation of Ti–Al rich phase. The EDS testing results of point 1 reveal that the IMCs contained 73.2 at% Al and 26.8 at% Ti, which were consistent with the element ratio of TiAl₃. The EDS results indicate that a spot of titanium alloy plate melted and dissolved into molten pool under the excessive heat input, which subsequently reacted with molten metal and resulted in the formation of TiAl₃ phase. According to Al–Ti binary phase diagram, various Al–Ti intermetallic compounds may be formed during the cooling process of the molten metal, such as TiAl₃, Ti₃Al, TiAl and Ti₃Al. However, previous literatures reveal that TiAl₃ phase is kinetically and thermodynamically more favorable to be formed among these above Al–Ti IMCs, verifying the rationality of experiment results in this paper. Besides, some Mg element and Si element were observed in the fusion area, which were mainly derived from Al alloy base metal and filler material, as indicated in table 1.

3.3. Microstructure of brazing area of Al/Ti joint

Figure 7 presents the BSE images of brazing areas (plotted by rectangles in figure 4) of Al/Ti joints with various welding parameters. It is obvious that the welding heat input plays a key role in the evolution of micromorphology of brazing area. As illustrated in figure 7(a), a thin and continuous interfacial reaction layer
with thickness of 1 μm was formed at the interface of fusion area/Ti alloy at finite heat input (with current of 70A). And the interfacial reaction layer was characterized by lamellar micromorphology. As the heat input increased (with current of 80A), the thickness of intermetallic compound layer increased to about 2 μm and the reaction layer morphology was transformed into serrated structure, as depicted in figure 7(b). With the enhancement of heat input (with current of 90A), intense interfacial reaction occurred between weld seam and
Ti alloy owing to the increased surface activity of Ti alloy plate, which resulted in the formation of clubbed IMC layer, as presented in Figure 7(c). Besides, it can be found that some fractured clubbed IMCs were distributed near the interface of weld seam and Ti alloy, owing to the strong electromagnetic stirring of arc. Figure 7(d) indicated a serrated IMC layer was formed and accompanied by crack. Compared with figures 7(a)–(c), the maximum thickness of reaction layer was up to 6.25 μm with the current of 100A. It is apparent that the excessive growth of reaction layer led to the increase of stress concentration in the brazing area, and finally led to the formation of crack. Both thick brittle IMC layer and crack will degrade the mechanical performance of Al/Ti joint.

Figure 8 shows the typical concentration profiles of Ti, Al, Mg, and Si alloy elements across the brazing area of Al/Ti joint (with current of 90A). As shown, Al element and Mg element were mainly concentrated in the side of fusion area, whereas Ti element was mainly distributed in the side of Ti alloy plate. However, of particular note is that some Ti element was also segregated in the IMCs layer, revealing that some Al-rich phase occurred during TIG welding-brazing process. The EDS results of point 1 show that the IMCs layer contained 76.6 at% Al and 23.4 at% Ti, indicating the formation of TiAl3 phase. In addition, it can be found that some aggregation of Si element was observed near the interface of weld seam and Ti alloy plate, which was mainly introduced from Al alloy filler wire.

3.4. Micro hardness
Figure 9 present the typical microhardness measurement positions of Ti/Al weldment obtained with current of 90A and 100A. And the micro hardness distributions across the transverse sections of Al/Ti joint obtained with current of 90A and 100A are illustrated in Figure 10. The approximate average micro hardness value of Ti alloy base plate was 125HV. As presented in figure 10(a), the micro hardness of brazing area increased to 143HV, which was far greater than that of parent metal. The obvious increase in hardness is mainly due to the formation of brittle and hard IMCs layer in brazing area. However, the micro hardness value of fusion area dramatically decreased to about 95HV because of general grain coarsening. Similar trends in hardness value were reported by Wang et al [28]. Figure 10(b) indicates that, as the welding current increased to 100A, the evolution of hardness values of brazing zone was consistent with that of the joint obtained under current of 90A. However, it is noteworthy that the hardness distribution of fusion area changed obviously. The average micro hardness of fusion zone increased to about 114HV and accompanied with significant fluctuation. As indicated in figure 5(d),
Figure 8. The typical concentration distributions of alloy elements of brazing area (with current of 90A).

Figure 9. The typical microhardness measurement positions of Ti/Al weldment obtained with current of 90A and 100A.

Figure 10. The typical microhardness distributions across the transverse sections of Ti/Al weldment obtained with current of 90A and 100A.
3.5. Tensile shear strength and fracture characteristics

The average tensile shear strength of Al/Ti joints obtained with different parameters are depicted in Figure 11. It is apparent that the welding current affected the joining strength of Al/Ti joint. In general, the mechanical properties increased first and then decreased with the improvement of welding current. When the heat input was insufficient, the metallurgical reaction in the brazing zone was not sufficient and resulted in the poor mechanical performance. The optimal Ti/Al weldment with the maximum welding strength of 192 MPa was obtained under the current of 90 A. As the welding heat input continued to increase, crack initiated and propagated in the brazing zone and eventually led to a decrease in mechanical performance, as depicted in Figure 7(d).

Figures 12 and 13 respectively show the typical fracture paths and corresponding fracture appearances (weld seam side) of Ti/Al weldments obtained with varying welding parameters. Table 3 lists the EDS analysis results of fracture appearances of Ti/Al weldments marked in Figure 13. It is evident that the fracture characteristics of joint are closely related to the welding heat input. With a low welding current of 70 A, insufficient heat input unable to achieve sufficient metallurgical bonding. The EDS analysis indicated that flat area at Point 1 containing
71.9 at% Al and 28.1 at% Ti was TiAl₃ interfacial reaction layer, while the rugged area at Point 2 was weld seam containing 98.2 at% Al and 1.8 at% Mg. The fracture morphology and EDS results revealed that fracture occurred across the brazing area. Figure 13(b) shows that the area percentage of rugged area (weld seam with 97.4 at% Al and 2.6 at% Mg) increased gradually, while that of flat area (IMCs layer with 77.4 at% Al and 22.6 at% Ti) decreased. With optimized welding heat input (90A), the fracture morphology of joint was characterized by typical dimples and tearing ridges, indicating considerable restrain of crack propagation and excellent plastic deformation capacity, as presented in figure 13(c). It is apparent that fracture occurred in the weld seam adjacent to the interface of Al/Ti. However, the fracture appearance of Al/Ti joint, with current of 100A, exhibited the features of brittle fracture with enlarged smooth region. According to EDS analysis and microscopic features (figure 7(d)) as above, it can be inferred that the fracture mainly occurred in the brazing zone adjacent to Ti alloy base metal.

In general, the optimum mechanical performance was gained with a suitable thickness of interfacial reaction layer. The TiAl₃ intermetallic compound layer at the interface of weld seam/Ti alloy was essential for promoting metallurgical joining. Nevertheless, the excessive generation of TiAl₃ intermetallic compounds impeded the continuous increase of mechanical properties.

### Table 3. EDS analysis results of fracture surfaces of Ti/Al weldments marked in figure 13.

| Elements (at%) | Al  | Ti   | Mg  |
|---------------|-----|------|-----|
| Point 1       | 71.9| 28.1 | —   |
| Point 2       | Bal.| —    | 1.8 |
| Point 3       | 77.4| 22.6 | —   |
| Point 4       | Bal.| —    | 2.6 |
| Point 5       | Bal.| —    | 1.0 |
| Point 6       | 76.3| 23.7 | —   |
| Point 7       | Bal.| 2.9  | 0.8 |

Figure 13. The typical fracture appearances (weld seam side) of Ti/Al weldments obtained with varying welding parameters.
3.6. Joint formation mechanism

According to the experiment observation and analysis as above, a sketch map of interfacial reaction is depicted in figure 14. The joint formation mechanism can be interpreted as follows:

(i) Under the action of arc heating, the Al alloy base plate and filler metal melted and resulted in the formation of axiolitic molten pool. Zn foil with low melting point melted and aggregated in the interface of molten pool and Ti alloy. Besides, some of the Ti atoms dissolved into molten metal and mixed with other atoms, as presented in figures 14(a) and (d).

(ii) Under the agitation of TIG arc, Zn atoms diffused into the central area of molten pool, as illustrated in figure 14(b). And figure 14(e) indicates that a thin TiAl3 IMCs layer precipitated at the interface of molten pool and Ti alloy. Literatures reveal that TiAl3 phase is kinetically and thermodynamically more favorable to be formed among Al–Ti IMCs (TiAl3, TiAl2, TiAl and Ti3Al) due to the lowest Gibbs energy variation, which are consistent with the present study.

(iii) As diffusion and interfacial reactions continued, Zn atoms were sufficiently diffused into various regions of the molten pool and thicker IMCs layer were formed at the brazing area, as presented in figures 14(c) and (f).

4. Conclusions

In this paper, the mechanical and microstructure analysis of welding-brazing of Al/Ti butt joint with Zn foil additive was investigated. And the joint formation mechanism was illuminated in terms of experiment observation and analysis. The main conclusions were drawn as follows:

(1) The TIG welding-brazing process was successfully developed to join 5052 Al alloy and Ti6Al4V alloy. The joint morphology was affected by welding heat input.

(2) With low heat input, a mass of residual Zn and thin TiAl3 IMCs layer occurred in the fusion area and brazing area respectively. And with optimal heat input, both the homogeneous diffusion of Zn atoms and the formation of clubbed interfacial reaction layer were beneficial to enhance joint performance.

(3) The optimal Ti/Al weldment with the maximum joining strength of 192 MPa was obtained under the current of 90A. Fracture occurred in the weld seam area adjacent to the interface of Al/Ti and the fracture morphology was characterized by typical dimples and tearing ridges.

Acknowledgments

The authors gratefully acknowledge the financial support provided by the Yangtze Normal University (Grant No. 0107/011160023).
Conflicts of interest

No potential conflict of interest was reported by the authors.

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References

[1] Zhang Y F, Huang J H, Ye Z, Cheng Z, Yang J and Chen S H 2018 Influence of welding parameters on the IMCs and the mechanical properties of Ti/Al butt joints welded by MIG/TIG double-sided arc welding Brazing J. Alloys Compd. 747 764–71
[2] Carlton H D, Klein K D and Elmer J W 2019 Evolution of microstructure and mechanical properties of selective laser melted Ti–5Al–5V–3Mo–3Cr after heat treatments Sci. Technol. Weld. Join. 24 465–73
[3] Xu Z W, Li Z W, Xu L and Yan J C 2019 Reduction of intermetallic compounds in ultrasonic assisted semi-solid brazing of Al/Mg alloys Sci. Technol. Weld. Join. 24 163–70
[4] Lv S X, Cui Q L, Huang Y X and Jing X J 2013 Influence of Zr addition on TIG welding–brazing of Ti–6Al–4V to Al5083 Mater. Sci. Eng. A 568 150–8
[5] Chen S H, Li L Q, Chen Y B, Dai J M and Huang J H 2011 Improving interfacial reaction nonhomogeneity during laser welding–brazing aluminum to titanium Mater. Des. 32 4408–16
[6] Chen Y B, Chen S H and Li L Q 2010 Influence of interfacial reaction layer morphologies on crack initiation and propagation in Ti/Al joint by laser welding–brazing Mater. Des. 31 227–33
[7] Song Z H, Nakata K, Wu A P and Liao J S 2013 Interfacial microstructure and mechanical property of Ti6Al4V/Al6061 dissimilar joint by direct laser brazing without filler metal and groove Mater. Sci. Eng. A 560 111–20
[8] Chen S H, Li L Q, Chen Y B and Huang J H 2011 Joining mechanism of Ti/Al dissimilar alloys during laser welding–brazing process J. Alloys Compd. 509 891–8
[9] Tomashchuk I, Sallamand P, Cicala E, Peyer P and Grevey D 2015 Direct keyhole laser welding of aluminum alloy AA5754 to titanium alloy TiAlV J. Mater. Process. Technol. 217 96–104
[10] Casalino G, Mortello M and Peyre P 2015 Yb–YAG laser offset welding of AA5754 and T40 butt joint J. Mater. Process. Technol. 223 139–49
[11] Chen Z W and Yazdanian S 2015 Microstructures in interface region and mechanical behaviours of friction stir lap Al6060 to Ti–6Al–4V welds Mater. Sci. Eng. A 634 37–45
[12] Ma Z W, Jin Y Y, Ji S D, Meng X C, Ma L and Li Q H 2019 A general strategy for the reliable joining of Al/Ti dissimilar alloys via ultrasonic assisted friction stir welding J. Mater. Sci. Technol. 35 94–9
[13] Wu A P, Song Z H, Nakata K, Liao J S and Zhou L 2013 Interface and properties of the friction stir welded joints of titanium alloy TiAlV with aluminum alloy 6061 Mater. Des. 71 85–92
[14] Assari A H and Eghbali B 2019 Solid state diffusion bonding characterizations at the interfaces of Ti and Al layers J. Alloys Compd. 773 50–8
[15] Ren J W, Li Y and Feng T 2002 Microstructure characteristics in the interface zone of Ti/Al diffusion bonding Mater. Lett. 56 647–52
[16] Chang S Y, Tsao L C, Lei Y H, Mao S M and Huang C H 2012 Brazing of 6061 aluminum alloy/Ti–6Al–4V using Al–Si–Cu–Ge filler metals J. Mater. Process. Technol. 212 8–14
[17] Chen X G, Xie R S, Lai Z W, Liu L, Zou G S and Yan J C 2016 Ultrasonic-assisted brazing of Al–Ti dissimilar alloy by a filler metal with a large semi-solid temperature range Mater. Des. 95 296–305
[18] Froneczek D M, Wozewoda–Budka J, Chulist R, Sypien A, Korneva A, Szulc Z, Schell N and Zieba P 2016 Structural properties of Ti/Al clads manufactured by explosive welding and annealing Mater. Des. 91 80–9
[19] Froneczek D M, Chulist R, Szulc Z and Wozewoda–Budka J 2017 Growth kinetics of TiAl3 phase in annealed Al/Ti/Al explosively welded clads Mater. Lett. 198 160–3
[20] Zhang H M, Chao Y J and Luo Z 2016 Effect of interlayer on microstructure and mechanical properties of Al–Ti ultrasonic welds Sci. Technol. Weld. Join. 22 79–86
[21] Wang S Q, Patel V K, Bhole S D, Wen G D and Chen D L 2015 Microstructure and mechanical properties of ultrasonic spot welded Al/Ti alloy joints Mater. Des. 78 53–61
[22] Zhang C Q, Robson D and Prangnell P B 2016 Dissimilar ultrasonic spot welding of aerospace aluminum alloy AA2139 to titanium alloy TiAl6V4 J. Mater. Process. Technol. 231 382–8
[23] Song J L, Lin S B, Yang C L and Fan C L 2009 Effects of Si additions on intermetallic compound layer of aluminum–steel TIG welding–braze joint J. Alloys Compd. 488 217–22
[24] Sun Q J, Li J Z, Liu Y B, Li B P, Xu P W and Feng J C 2017 Microstructural characterization and mechanical properties of Al/Ti joint welded by CMT method–assisted hybrid magnetic field Mater. Des. 116 316–24
[25] Xue J Y, Li Y X, Chen H and Zhu Z T 2018 Effects of heat input on wettability, interface microstructure and properties of Al/steel butt joint in laser–metal–inert gas hybrid welding–brazeing J. Mater. Process. Technol. 255 47–54
[26] Tan C W, Yang J, Zhao X Y, Zhang K P, Song X G, Chen B, Li L Q and Feng J C 2018 Influence of Ni coating on interfacial reactions and mechanical properties in laser welding–brazing of Mg/Ti butt joint J. Alloys Compd. 764 186–201
[27] Zhao X Y, Tan C W, Xiao L Y, Xia H B, Chen B, Song X G, Li L Q and Feng J C 2018 Effect of the Ni coating thickness on laser welding–brazing of Mg/steel J. Alloys Compd. 769 1042–58
[28] Wang H D, Yuan X J, Li T, Wu K L, Sun Y Q and Xu C 2018 TIG welding–brazing of Ti6Al4V and Al5052 in overlap configuration with assistance of zinc foil J. Mater. Process. Technol. 251 26–36