A review of dissimilar welding for titanium alloys with light alloys

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Abstract. Titanium (Ti) alloys are widely used in industrial manufacturing, medical treatment, vehicles, and other fields. When welded with other alloys, due to great differences in physical and chemical properties of these materials, cracks easily appear in the joint, and obtaining stable welded joints is difficult. Results show that brittle intermetallic compounds (IMCs) formed in the welding process could reduce the plasticity of the joint. This review aimed to provide a comprehensive overview of the recent progress in welding and joining of Ti alloy and light alloys and to introduce current research and application. The methods available for welding Ti alloy and light alloys included fusion welding, brazing, diffusion bonding, friction welding and reactive joining. In this study, control methods of brittle IMCs in the welding process of Ti and other alloys and various improvement measures studied at home and abroad are described.

Keywords: titanium alloys / magnesium alloy / aluminum alloy / joint / intermetallic compounds

1 Introduction

Titanium (Ti) alloys have been widely used in the fields of industrial manufacturing, shipbuilding, and stomatology because they possess low density, high strength, and corrosion resistance. Especially in the field of aerospace, large amounts of Ti alloys are required. In addition, the use of Ti alloy structural parts reduces the weight of aviation products [1]. The composite structure of titanium alloy and other dissimilar materials has great significance and broad prospect for realizing a lightweight structural design and reducing cost. For example, the heat sink of aircraft cabin, seat guide rail, wing honeycomb sandwich, and high-speed train carriage can adopt a Ti/aluminum (Al) composite structure [2]. Thus, higher requirements for Ti/Al composite structure are put forward. Airbus uses Ti/Al composite structure to design aircraft seat guide rail to reduce weight and manufacturing cost [3]. As shown in Figure 1, laser-welded riveted skin-stringer joint was applied to aircraft bodies, leading to lower costs and a decreased weigh [4]. To reduce aircraft weight, maintain high specific strength and good fatigue resistance, NASA YF-12 fighter plane uses Ti/Al honeycomb core composite plate to build wings [5]. As shown in Figure 2, the aircraft adopts Borsic/Al-Ti honeycomb core composite plate as wing skin, which is made of Borsic/Al panel, Ti-3Al-2.5V honeycomb core, TC4 frame and strengthening plate [6].

The weldability of Ti alloys with other dissimilar metals mainly depends on their physical and chemical properties. When the physical properties differ greatly, for example, when the melting points of the two materials differ greatly, melting cannot be carried out at the same time, thereby resulting in the loss of low melting point materials, burning or evaporation of alloy elements, and poor weld formation. The difference in the thermal conductivity and linear expansion coefficient between these materials leads to large deformation and internal stress at the joint after welding. When the chemical properties differ greatly, brittle intermetallic compounds (IMCs) are easy to form, thereby resulting in the plasticity and high temperature performance of the joint worse. Thus, the welding between Ti and other alloys is greatly difficult. The oxidation of Ti alloys and dissimilar metals at high temperature also seriously affects the welding quality. In addition, oxidation products can significantly reduce the strength and plasticity of weld metals. At the same time, titanium easily absorbs hydrogen, oxygen, and nitrogen at high temperature, the joint is easily polluted by these gases, and embrittlement even produces pores.

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The difficulty about welding of dissimilar alloys Ti/Al is mainly due to the brittle IMCs produced in the joint. However, the fusion welding of Ti/Mg dissimilar metals cannot be realized due to the large difference in density between the two metals. Therefore, welding of Ti/Mg dissimilar metals is necessary to fill the intermediate layer in the welding process of Ti/Mg metals to realize the welding of Ti/Mg. However, the problem of producing Ti/Mg brittle IMCs will persist in the process of filling the intermediate layer. Therefore, welding of Ti and dissimilar alloys is difficult. To avoid common welding defects and ensure the mechanical properties and corrosion resistance of welding, reasonable welding process and appropriate welding method must be formulated to ensure the welding quality.

2 Fusion welding

Precise control of welding heat input is required in the fusion welding process of Ti alloys and dissimilar metal. Laser-welded, electron beam welding (EBW), and tungsten inert gas (TIG) welding are widely used.

2.1 Direct high energy beam welding

Wu et al. [7] developed a lap configuration laser-welded unfilled TC4 titanium alloy and aa6060 Al alloy. The laser beam only penetrates the lower Al plate when the Ti plate is on top. As shown in Figure 3, severe crack defects, mainly hot cracks, are formed in the joint. According to the EDS analysis results, the crack was mainly caused by the formation of a large number of TiAl, TiAl3, and other IMCs in the weld. Thus, the brittleness of the joint was improved. Peyre et al. [8] studied the laser-welding of T40 Ti alloys to a5754 Al alloys. The laser focused on the upper side of the Al plate, and the joint fracture occurred after welding. The fracture occurred on the TiAl3 compound layer in the fusion zone of the Al side. The serrated TiAl3 brittle phase promoted crack initiation and reduced the mechanical properties of the joint. Ping and Chen [9] of Huazhong University of Science and Technology carried out laser butt welding of TC4 and 5083 Al alloys without fillers. After laser beam focusing on the interface of Ti/Al cracks appeared on the welded joint. The microstructure of the weld consisted of α-Ti, TiAl3, Ti3Al, TiAl, Ti2Al and α-Al. The tensile strength of Ti/Al joint decreased with the increase in Ti-Al IMCs. Tomashchuk et al. [10] carried out laser direct welding of 5754 Al alloys and TC4 Ti alloys and found that the fracture started in the fusion zone with high Al content in the butt joint of Ti/Al (Fig. 4). Therefore, the formation of a large number of Ti-Al IMCs in the joint main caused weld embrittlement and poor mechanical properties of the joint. Therefore, the formation of brittle Ti-Al IMCs should be restrained or avoided to obtain good properties of Ti/Al joints. This research shows that a large number of cracks appear in the Ti/Al joint without fillers, mainly due to the formation of a large number of brittle Ti-Al IMCs in the welding. This main problem should be solved in the follow-up research.

Gasalio et al. [11,12] developed laser-welded unfilled 5754 Al and T40 Ti alloys in the form of butt joint and beam offsetting to the Ti side. When the laser offset on Ti is 0.75 mm, the microstructure of the weld is mainly TiAl3 phase, the tensile strength of the joint can reach 191 MPa, and the fracture occurs in the fusion zone of Al side. Qi et al. [13] carried out electron beam partial Ti side welding of Ti6321 Ti and 5083 Al alloys. When the electron beam offset on Ti is 0.6 mm, no welding defects are found on the joint. The tensile strength of the joint can reach 219 MPa, and the fracture is located in the fusion zone on the Al side. The reason is that the thermal conductivity of Al is much larger than that of Ti alloys. The molten pool formed by heat conduction on the Al side is rapidly cooled, and the columnar structure is formed in the fusion zone on the Al side and grows along the direction perpendicular to the weld center. Guo et al. [14] completed the connection of TC4 Ti alloys and 6082 Al alloys by laser offset welding on the Al side. Ti/Al joints obtained good tensile strength without cracks and pores. The tensile strength was 153 MPa. The Ti/Al joint had a brittle cleavage fracture, and the fracture occurred in the Ti-Al IMCs, where the brittle phases are TiAl and TiAl3. Wang et al. [15] welded 6061 Al and TC4 Ti alloys by offsetting laser on Al side. The maximum tensile strength of Ti/Al joint was 192 MPa.
when the laser beam offset was 1.3 mm, and the fracture mode was ductile. Lan et al. [16,17] welded 6061 Al and TC4 Ti alloys by laser bias on the Al side. The effect of welding speed on the Ti/Al joint was studied. The results showed that if the welding speed was high, then no fusion occurred on the Ti/Al joint. If the welding speed was low, a great number of Ti-Al IMCs would be formed in the Ti/Al joint, and even cracks would appear. Chen [18] welded 6061 Al and TC4 Ti alloys by laser beam offset on Ti. The maximum tensile strength of Ti/Al joint is 199 MPa, and the fracture occurs at the Al side. A great deal of Ti-Al IMCs are observed in the Ti/Al joint. Song [19], Chen et al. [20], and Maikov et al. [21] found that the maximum tensile strength of Ti/Al joint increased to 272 MPa when the laser beam offset on the Ti increased. Guo et al. [22,23] carried out laser butt welding experiments on LD2 Al alloys and TC4 Ti alloys. The results show that the Ti/Al joint with good quality can be obtained when the laser is applied on the Ti side, and the tensile strength can reach 242 MPa. The Ti/Al joint breaks at the Al side.

Kurytsev [24] used CP-Ti and AA2024 Al alloys for laser welding and obtained a well formed joint. The microstructure of the welded joint is Ti₃Al phase, and the tensile strength of the joint is in the range of 80–120 MPa. Lee et al. [25] laser welded Ti/Al dissimilar metals in the form of lap joint (Ti placed on the upper side). He found that the brittle IMCs of Al₃Ti and Al₅Ti in Ti/Al joint can be reduced when the welding speed is 50 m/min. Qu et al. [26,27] used electron beam welding on 7075 Al and TC4 Ti alloys and placed the Al plate on the upper side. A thin transition layer is formed in the Ti/Al joint. The Ti-Al IMC grows from Ti side to Al side, and the main phase is Ti₅Al₃. The formation of other Ti-Al IMCs was inhibited by electron beam shift. These studies show that the offset of heat source reduces the content of Ti-Al IMC in the weld, thereby reducing the brittleness of the joint and improving the tensile strength of the joint. However, welding parameters need to be strictly controlled for heat source offset. If the heat input is extremely high, then cracks easily occur in the joint. Moreover, the formation of brittle Ti-Al IMCs cannot be completely avoided by heat source offset welding without filler metals, and the mechanical properties of joints need to be improved.

On the basis of the research on high energy beam offset welding, Leo et al. [28] carried out laser welding Ti/Al and then performed 350°C and 450°C post weld heat treatment. In the welding process, the Ti-biased side (1 mm) welding technology was used to limit the formation of Ti-Al brittle IMCs, and a good joint was obtained (Fig. 5). After 350°C heat treatment after welding, the tensile strength of Ti/Al joint is improved to a certain extent, reaching 200 MPa. However, heat treatment at 450°C decreases the strength. The joint strength improves when the temperature is increased, consistent with the conclusion of reference. The results show that the elongation of Ti/Al joint is increased by heat treatment, and the tensile strength of the joint is improved. The main metal compounds in the weld after PWHT are Ti₃Al and Ti₅Al. However, when the heat treatment temperature is extremely high, the Ti₅Al₃ phase increases, thereby reducing the mechanical properties of Ti/Al joint. Therefore, controlling the heat treatment temperature is necessary.

The welding parameters and test results of these studies are summarized in Table 1. For the Ti/Al offset welding without filling heat source, the tensile strength of Ti/Al joint is improved by heat source offset. This condition is achieved because in the welding process of heat source offset, the melting amount of single side base metal is reduced, and the fusion ratio of Ti/Al in the weld is adjusted, thereby inhibiting the formation of Ti-Al brittle IMCs to a certain extent. The post weld heat treatment process improves the joint tensile strength by increasing the joint elongation. However, Ti-Al IMCs can still be formed in Ti/Al joints with heat source offset. The tensile strength and other mechanical properties of joints can be improved by other methods.
2.2 Laser welding with filler metals

Majundar et al. [29] used Nb as the interlayer to study the laser welding of Ti/Al dissimilar materials. The melted Nb layer acts as a diffusion barrier to dissolve Ti and Al elements in the molten pool and promotes the good welding conditions between Ti and Al. Finally, a Ti/Al joint with tensile strength of 127 MPa is obtained. Compared with the previous test results without interlayer, a large number of cracks were not observed in the joint shown in Figure 6. The figure shows that the addition of interlayer inhibits the formation of Ti-Al IMCs and improves the quality of Ti/Al joint. However, the tensile strength of the joint is not very high, indicating that the formation of Ti-Al brittle IMCs cannot be avoided by adding an interlayer.

Ni et al. [30] used Al-12Si welding wire as filler metals for laser welding of TC4 Ti and 5056 Al alloys. The laser is focused on the welding wire. Under the thermal action of the laser, the welding wire is completely melted, whereas the Ti and Al alloys are slightly melted. The needle or bud-like Ti-Al-Si layer and continuous compound layer mainly composed of Ti-Al IMCs are formed in the weld. The average tensile strength of the joint is 298.5 MPa, and the fracture occurs in the fusion zone of the Ti side. With the addition of Al-12Si wire, the Ti-Al-Si ternary compound is formed in the weld, and the tensile strength of the joint is evidently increased. Therefore, the mechanical properties of Ti/Al joint can be significantly improved by reasonable selection of filler metals.

The solid solubility between Ti/Mg is very small, and no IMCs are formed different from Ti/Al. Therefore, the traditional welding method cannot easily realize the reliable connection between Ti and Mg. The effective bonding of Ti/Mg dissimilar metals can be realized by filling the interlayer.

Table 1. Test results of unfilled titanium/aluminum joints.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Strength (MPa)</th>
<th>Welding methods</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA5754+TC4</td>
<td>200</td>
<td>Laser welding</td>
<td>PWHT350 °C</td>
</tr>
<tr>
<td>AA5754+T40</td>
<td>191</td>
<td>Laser beam offset Ti 0.75 mm</td>
<td></td>
</tr>
<tr>
<td>AA2024+CP-Ti</td>
<td>80-120</td>
<td>Welding speed150 mm/s</td>
<td></td>
</tr>
<tr>
<td>AA5083+Ti6321</td>
<td>219</td>
<td>Electron beam welding</td>
<td>Electric beam offset 0.6 mm</td>
</tr>
</tbody>
</table>

Fig. 5. Macroscopic morphology of laser direct welded Ti/Al joint (Reproduced with permission from Ref. [28] Copyright 2018 Elsevier).

Fig. 6. Laser-welded Joint of Ti/Al (Reproduced with permission from Ref. [29] Copyright 1997 Springer).
Fig. 7. Macroscopic morphology before and after adding copper interlayer: (a) before adding; (b) after adding copper interlayer (Reproduced with permission from Ref. [32] Copyright 2020 CNKI).

Zang et al. [31] added an Al interlayer between Mg and Ti dissimilar metals. The TiAl3 phase is formed in the laser direct irradiation region. The thickness of the TiAl3 reaction layer has slightly changed with the increase in the Al layer thickness. However, with the increase in the Al layer thickness, Mg/Al IMCs (Mg17Al12) have become more compact in the Mg side fusion zone. When the thickness of the Al layer is 0.05 mm, the maximum tensile strength can reach 2230 N/cm. Gu et al. [32] realized the butt laser welding of Ti/Mg by pulse laser and Cu interlayer addition. They found that the addition of Cu interlayer improves the microstructure of the weld interface and increases the content of Ti-Cu IMCs near the interface. As shown in Figure 7, the joint’s morphology is improved by adding the Cu interlayer. The Cu interlayer is melted completely, and a well formed Ti/Mg joint is obtained. When the thickness of the Cu interlayer reaches 30 µm, the tensile strength of the joint reaches 121 MPa. With the increase in the Cu interlayer thickness, the thickness of the Ti2Cu reaction layer at the interface gradually increases and becomes continuous. At the same time, the fracture position of the joint changes from the interface reaction layer to the weld zone. The increase in Mg2Cu brittle IMCs in the weld joint reduces the joint performance.

Compared with the commonly used filler metals, Zhang et al. [33] performed laser lap welding of Ni-coated TC4 Ti alloys and AZ31B Mg alloys, placed the Ti plate on the upper side, and obtained a good joint by using Ni electrodeposited layer as the intermediate element. A large amount of Ni enters the Ti alloy, which thickens the reaction layer again (Fig. 8). With the increase in laser power, the thickness of the reaction layer does not increase monotonically. When the laser power is 1500 W, the tensile strength can reach 144 N/mm.

3 Welding–Brazing

3.1 High-energy beam welding–brazing

Fusion brazing has the common characteristics of fusion welding and brazing. By continuously feeding welding wire to fill the joint, the low melting point alloy is in the melting state, whereas the Ti alloys remain unchanged. Therefore, the molten metal and welding wire infiltrate and spread the surface of Ti alloys and are connected together by diffusion and metallurgical reactions between atoms. This welding method is flexible and has high welding strength, but heat input should be strictly controlled.

For the welding of Ti/Al dissimilar metals, Lei et al. [34] used laser cladding Al-10Si-Mg filler metal to weld Ti/Al (Fig. 9). Figure 10 shows no defects on the Ti/Al joint after seven-layer deposition, and the microstructure distribution is uniform. The tensile strength can reach 240 MPa, and the fracture location is in the fusion zone of Al side. The microstructure of brazing interface between Ti-based metal and weld metal is α-Ti, grain Ti7Al5Si12, and Ti (Al, Si)3 with different shapes. The Ti7Al5Si12 phase inhibits the formation of Ti-Al brittle IMCs. Li et al. [35], Chen et al. [36], and Chen et al. [37,38] used Al12Si welding wire for laser fusion brazing of Ti/Al dissimilar metals. They found that the Si element diffuses into the brazing interface, and the diffusion behavior of Si atoms plays an important role in the formation of IMCs. The formation of Ti7Al5Si12 depends on the dissolution of Ti alloys and the segregation of Si atoms. Therefore, the formation of ternary compound Ti7Al5Si12 inhibits the growth of Ti-Al IMCs and improves the ductility of Ti/Al joint.

Wang et al. [39] carried out electron beam fusion brazing of TA2 pure Ti and 1060 pure Al with Al12Si welding wire. The tensile strength of the joint is 98.8 MPa. The results show that the interface structure of the weld is mainly TiAl3 and TiAl2. The content of Ti-Al IMCs in the joint is greatly reduced due to the small amount of melting of Ti alloys. Miao et al. [40] used bypass current metal inert gas (MIG) welding to weld TC4 Ti and AA6061 Al alloy filled Al5Si welding wire. The thickness of the metal compound layer formed by metallurgical reaction at the Ti side interface is 1.5–15 µm, which is mainly composed of TiAl3 and TiAl phases. The tensile strength of the joint can reach 196 MPa. Fusion brazing can effectively inhibit the formation of Ti-Al IMCs and improve the properties of the joint. Zhang et al. [41,42] of Beijing University of Science and Technology carried out MIG/TIG double-sided arc brazing of Ti/Al dissimilar metals with Al5Si wire. The microstructure of the weld is mainly Mg2Si diffused in α-Al matrix, and no Ti-Al IMCs are observed. The transition layer is thinner than that of traditional MIG welding because the heat input of MIG/TIG double-sided arc brazing is low and uniform. When the welding speed is 15 mm/s, the TIG welding current is 80–90 A, and the TIG welding position is 0 mm; the average tensile strength of the joint reaches 240.3 MPa. Compared with Al12Si welding wire, no Ti-Al-Si ternary compound is found on the joint. The bonding of the joint mainly depends on the brazing reaction on the surface of the Ti alloy. The Ti-Al IMC layer is very thin because of the small amount of melting on the Ti side. Although the fusion brazing joint cannot inhibit the formation of Ti-Al IMCs, the content of Ti-Al IMCs is greatly reduced, and the joint can still maintain high strength. Li [43] used the technology of cold metal transition assisted by an external longitudinal magnetic field to carry out the lap experiment of 6061-T6 Al and TA2 pure Ti. When the magnetic field excitation current is 1.0 A and the magnetic frequency is 10 Hz, the maximum tensile strength of Ti/Al joint is 4.105 kN, and the welded joint is fractured on the side of the Ti-based metal, showing an
evident ductile fracture mode. The results show that the external longitudinal magnetic field can significantly improve the weld formation of Ti/Al joint, enhance the wettability of weld metal on the surface of Ti alloys base metal, and increase the effective interface area. Wang et al. [44] used Al5Mg welding wire to weld pure Ti and 2024 Al alloys. A transition layer of 0.5–5 μm is formed at the interface of the joint. The main component is TiAl3 phase, which evidently inhibits the formation of Ti-Al IMCs. The tensile strength of Ti/Al joint is increased to 316 MPa.

Table 2 summarizes the test results of Ti/Al fusion brazing. Evidently, the tensile strength of Ti/Al fusion brazed joint is significantly improved compared with the welding process without filler material. The formation of
Ti-Al IMCs can be effectively inhibited or even avoided using appropriate filler materials and fusion brazing process to satisfy the requirements of high-strength properties. Ti/Mg joint with high tensile strength can be obtained by Ti/Mg fusion brazing. Tan et al. [45,46] used laser fusion brazing technology to connect Ti/Mg alloy with dissimilar metals by using AZ91 Mg alloy welding wire with higher Al content than AZ31B Mg alloy-based metal. Compared with AZ31 welding wire with the same composition as Mg alloy-based metal, the strength of the lap joint is greatly improved under different parameters in many tests, and the maximum strength reaches 2057 N. However, the tensile strength of Ti/Mg joint is only 1049 ± 227 N when Mg AZ31 welding wire with low Al content is used. Studies show that a continuous reaction layer is formed at the interface between the fusion zone and the Ti alloy when the AZ91 welding wire is used (Fig. 11). Tan et al. [47] carried out laser lap fusion brazing of Ti/Mg dissimilar metals by preset Al foil. The welding parameters were adjusted to obtain better weld formation, and the diffusion and bonding mechanism of the interface elements were studied. The results show that the addition of Al interlayer can improve the wetting and spreading of the weld and promote the metallurgical reaction of the interface. When the thickness of the Al interlayer is increased by 50 μm, the joint load is 1.8 times that of the original thickness, reaching 1010 N/cm. The number of the second phase in the weld increases with the increase in the thickness of the Al interlayer. When the network structure is formed, the weld becomes brittle and the tensile strength of the joint is reduced. Tan et al. [48] selected the AZ91 welding wire with 9% Al element content as filler metal and realized a reliable connection between AZ31B Mg and TC4 Ti alloys by laser melting brazing. They found that the tensile strength of the Ti/Mg joint filled with AZ91 welding wire reaches 1520 N. The Al element in the AZ91 welding wire can segregate to weld interface during laser rapid heating and cooling process and produce AlTi3 compound with Ti side. Figure 12 shows that the reaction layer is evidently improved with the increase in power. The thin interface reaction layer (less than 2 μm) is occluded with the molten metal of the Mg welding wire in zigzag shape. The interface metallurgical bonding is realized, and the thickness of the reaction layer is controlled within the range, thereby not affecting the tensile properties of the Ti/Mg joint.

The researchers combined the solder process with the method of plating metal layer on the base metal and obtained excellent joint. Caiwang Tan et al. [49] used AZ92 Mg-based welding wire to weld TC4 Ti alloys with Cu plating and AZ31B Mg alloys by laser lap welding. When the thickness of Cu coating is 10.6 μm, the tensile strength is 2314 N, and the fracture load of the Ti/Mg joint without coating is increased by 55%. Cu plating can improve the wettability and spreading ability of molten metal on the surface of Ti and improve the stability of the welding process. Caiwang Tan et al. [50,51] used AZ92 welding wire to study laser fusion brazing of TC4 Ti and AZ31B Mg alloys. They found that the tensile strength increases slightly with the increase in Ni coating thickness. The maximum tensile strength of Ti/Mg lap joint can reach 2430 N/cm when the coating thickness is 4 μm. When the thickness of Ni coating is more than 4 μm, the fracture mode changes from interface failure to fusion zone fracture. The interface bonding is low and the fracture performance of fusion zone is high. The further increase in Ni coating thickness slightly affects the deterioration of properties. The Ni coating and AZ92 welding wire are used to realize the reliable butt joint of Mg and Ti. The Ni coating can also improve the wetting and diffusion ability of filler metal on Ti matrix and promote the interface reaction.

Zhang et al. [52] realized the combination of AZ31B Mg and TC4 Ti alloys with Cu plating by laser fusion brazing process. When the laser power is 1300 W, the tensile strength of the Ti/Mg joint reaches 2314 N, and all samples fracture at the weld. At 1100 W laser power, the fracture surface is generally smooth. With the increase in laser power, tearing ridges and Ti3Al particles are evident on the fracture surface. Wu [53] et al. studied the laser fusion brazing of AZ31 Mg alloy butt joint with Ni plating on TC4 Ti alloys. When the thickness of Ni coating is 1.5 μm, the Ti/Mg joint breaks at the Mg side and the tensile strength reaches 3900 N. With the increase in Ni coating thickness, the microstructure of the joint changes from ultrathin Ti3Al layer to Ti3Ni + Ti3Al mixed layer. In addition, more Mg2AlNi ternary compounds are formed. Auwal et al. [54–56] and Liu et al. [57] carried out laser fusion brazing joint of TC4 plated with Cu-Ni and AZ31B Mg alloys filled with AZ92 welding wire. They found that with the increase in Cu coating thickness and the decrease in Ni coating thickness, the tensile strength initially increases and then decreases, and the maximum tensile strength reaches 2020 N, which is two times higher than that of Ti/Mg joint without electroplated coating. Figure 13 shows that the coated Ti/Mg joint has better joint appearance and section. Therefore, the feasibility of this process strongly depends on the electroplated Cu-Ni layer on the Ti plate to promote the wetting of AZ92 wire.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Filler Metal</th>
<th>Weld Method</th>
<th>Strength (MPa)</th>
<th>References</th>
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<tr>
<td>Al6061+TC4</td>
<td>Al-10Si-Mg</td>
<td>Laser weld</td>
<td>240</td>
<td>[35]</td>
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<tr>
<td>5A06+TC4</td>
<td>AlSi12</td>
<td>Laser weld</td>
<td>279</td>
<td>[37]</td>
</tr>
<tr>
<td>Al6061+TC4</td>
<td>AlSi12</td>
<td>Laser weld</td>
<td>241</td>
<td>[38]</td>
</tr>
<tr>
<td>AI1060+TA2</td>
<td>Al5Si</td>
<td>Laser weld</td>
<td>98.8</td>
<td>[39–42]</td>
</tr>
<tr>
<td>2024Al+Ti</td>
<td>Al-5Mg</td>
<td>Laser weld</td>
<td>316</td>
<td>[43]</td>
</tr>
</tbody>
</table>
Table 3 lists a summary of laser fusion brazing of TC4 Ti and AZ31B Mg alloys. In the process of Ti/Mg dissimilar metal fusion brazing, the use of Cu and Ni coating improves the wettability of molten metal on the surface of Ti alloys. Auwal used the two types of coatings together. The relationship between the thickness of these coatings and the strength of Ti/Mg joint was found through experiments. The selection of Mg-based welding wire containing Al element can prevent the formation of brittle IMCs in Ti/Mg joints and increase the joint strength of Ti/Mg joints. These processes improves the tensile strength of Ti/Mg joints.

3.2 Cold metal transfer

The cold metal transfer (CMT) technology exhibited by Fronius [58,59] in 2004 combines wire feeding motion with droplet transfer through a feedback control system, which realizes a spatter-free welding process. It is a new arc welding method to control welding heat input, especially for welding of thin plates. The main reason for the deterioration of joint performance caused by the evaporation of light metal during welding is the limitation of heat input controlled by the welding method [60,61]. Therefore, welding of Ti alloys and other metals by cold metal transfer welding is feasible.

Sun et al. [62] welded TA2 Ti alloys with 6061-T6 Al alloys by magnetic field composite CMT welding process. The tensile strength of the joint reaches 4.105 kN and breaks at the Ti-based metal. The results show that the fluidness of the Ti/Al joint is promoted by the magnetic field. Under the action of electromagnetic field, the grains of weld and HAZ are refined and Ti-Al IMCs are reduced. The microstructure of the IMC layer is TiAl3, and the thickness is reduced from 10 μm to 5 μm. However, due to the instability of the welding process, the external magnetic field may react on the welding process of Al/Ti dissimilar metals.

Cao et al. [63] realized the fusion brazing joint of TA2 Ti and AZ31B Mg alloys by CMT. They found that the lap joint with AZ61 Mg alloy welding wire has higher joint strength, and the cross-sectional morphology of the two joints is shown in Figure 14. The analysis shows that the multicomponent compound layer including Ti3Al, Mg17Al2, and Mg0.97Zn0.03 is formed at the brazed joint surface. Meanwhile, the diffusion behavior of Al and Zn elements existing in the base metal and welding wire of Mg alloys is found at the interface, which is considered an important factor to promote the reliable connection of the joint. Wang et al. [64,65] simulated the temperature field of Ti/Mg dissimilar metal CMT welding by using the finite element model. They found that the temperature field distribution on both sides of Ti/Mg was asymmetric under CMT condition, and the temperature rise and temperature decrease of Mg side were fast. The results show that the welding heat input increases with the increase in wire feeding speed, and the reaction amount of Ti at the interface increases.
3.3 Hybrid welding–brazing

Laser arc hybrid welding has better energy utilization and working condition adaptability due to the interaction between laser and arc; it has good application prospect in the field of dissimilar metal welding. Compared with arc welding, laser arc hybrid welding has the advantages of high-speed welding and high efficiency. Greater penetration can be obtained without groove due to the keyhole effect of laser. Compared with laser welding, the laser absorption efficiency of the base metal can be improved due to the preheating effect of the arc [66–68].

Zhu et al. [69] used laser TIG composite heat source to weld AA6061 Al and TC4 Ti alloys. The Ti/Al joint with an average tensile strength of 230 MPa was obtained by focusing the laser arc on the Ti side. The uniformity angle of the layer of the Ti/Al joint was improved. Wang [70] carried out the fusion brazing experiment of 6061T6 Al and TC4 Ti alloys with laser MIG composite heat source and obtained Ti/Al joint with good performance (Fig. 15). Although Al12Si welding wire is filled, the filling amount of Al12Si welding wire is limited due to the unprocessed groove and reserved gap of Ti/Al plate. In addition, under the condition of rapid cooling, the Si atom diffusion in Ti/Al joint is insufficient, thereby resulting in a large amount of TiAl3 IMCs in the weld.

Zhang et al. [71,72] realized the fusion brazing of 5A06 Al and TC4 Ti alloys by MIG-TIG double-sided arc welding (MIG welding on the front) and Al6Si welding wire. The results show that the tensile strength of Ti/Al joint (Fig. 16) is 250 MPa, which is slightly higher than that of traditional MIG welding joint. The results show that the formation of the weld is evidently improved by uniform heat input. The interfacial layer near the Ti side is regular. The IMCs in the weld is composed of α-Al and Al-Mg2Si Si phases, thereby reducing the formation of Ti-Al IMCs.

4 Brazing

Brazing uses molten liquid solder to wet both sides of the base metal to achieve Ti/Al dissimilar metal connection. Compared with fusion welding, the welding stress during brazing is smaller, and the formation of brittle IMCs can be avoided by changing parameters, such as solder ratio and welding time, to realize the effective connection between Ti and other alloys [73].

4.1 Vacuum brazing

The research on brazing technology of Al Ti dissimilar metals has been carried out previously. In the late 1980s, Japanese scholar Takemoto and Okamoto [74] prepared and adopted Al-30Ag-10Cu, Al-10Si-Mg, Al-10Cu-8Sn, and Al-Cu-Mn-Cr alloy solders by adding Cu, Ag, Si, and other elements to pure Al. The brazing joint of Ti/Al dissimilar metals was successfully realized. This method can reduce the melting point of solder by adding alloying elements, thereby laying a foundation for the research of Ti/Al dissimilar metal brazing technology in solder preparation.
The oxide film on its surface hinders the interaction between the solders and between the filler metal and the base metal given that the powder solder is easy to oxidize. Therefore, Lee et al. [75] initially transformed the solder into foil, and then brazed the Al and Ti. The selected filler metal is AlSi10Mg, and the brazing temperature is controlled in the range of 580 °C–640 °C. Compared with powder solder, foil solder can effectively reduce the adverse effect of oxide film on the welding process. The composition of the interfacial reaction layer is Ti₆(Al, Si)₂₃ near the Al side and Ti₇Al₅Si₁₂ near the Ti side. Controlling the welding process is difficult because of the slight difference between the melting point of Al-based filler metal and Al-based metal. Subsequently, Solin et al. [76] prepared Al-Si-10Mg foil solder by reducing the content of Si in the solder and increasing the content of Mg element. The welding experiment of Ti/Al dissimilar metals shows that the adjustment of alloy element composition reduces the melting point of the solder to reduce the brazing temperature to a certain extent. The adverse effects of IMCs formed by the reaction between filler metal and base metal on the properties of Ti/Al joint cannot be avoided due to the formation of discontinuous Ti₇Al₅Si₃ and continuous Ti₇Al₅Si₁₂ IMCs at the interface. In addition, the formation mechanism of different IMCs in the joint still needs to be further studied, which is also one of the key areas in the research of dissimilar metal welding.

Chinese scholars have also carried out the research on metal vacuum brazing. Qu et al. [77] carried out brazing of Ti/Al dissimilar metals in the form of foil solder by adding a small amount of Mg element to Al-11.5Si alloys. They found that this process can reduce the melting point of solder and promote the diffusion reaction between filler metal and base metal. However, the IMCs formed by the reaction between filler metal and base metal at the interface still mainly affect the joint performance.

To further reduce the effect of IMCs on the joint properties, Chen et al. [78], Zhao and Kang [79] and Kang et al. [80] added Sn element to the filler metal to study the brazing of Ti/Al dissimilar metals. Sn and Ga, which are more metallic than Al, occupy Al atoms in Ti₃Al, TiAl, and TiAl₃ phases, inhibiting the formation of ternary IMCs and reducing the residual stress of the joint. Chen et al. compared the test results before and after adding Sn element into Al-Si-Zn-Cu-Ni filler metal, and found that the main constituent phases CuAl₂ and Ti₇Al₅Si₁₂ in the weld did not change. Although the formation of Ti-Al IMCs was inhibited, the CuAl₂ brittle phase was formed. In addition to Sn and Ga, S.Y. Chang et al. [81] studied the effect of Cu and Ge elements. The vacuum brazing of TC4 Ti and 6061 Al alloys was realized at 530 °C by using Al₅Si₇Cu₉Ge low melting point solder and by adding rare earth elements (La + Pr, 0.1% in total) into the solder. The results show that the addition of rare earth elements reduces the temperature of solids, and liquids would reduce the interfacial reaction energy and promote the metallurgical reaction between the base metal and the liquid solder on both sides. As shown in Figure 17, a ternary IMC Al₅Si₇Ti₇ with a width of approximately 3–6 μm is formed at the interface of the filler metal Ti. Compared with the filler metal without rare earth element, the tensile strength of Ti/Al joint increases from 20 MPa to 51 MPa.

4.2 High-frequency induction brazing

Induction brazing is a brazing technology in which the metal workpiece to be welded is placed in the induction coil, and the induction electromagnetic field is generated by high-frequency alternating current. Wang et al. [82] connected LF21 Al and Ti alloy (TC4, TA1, TA2) pipes by high-frequency induction brazing with self-developed filler metal and matched flux. The results show that the high frequency induction brazing time is very short. Thus, the time to form a large number of IMCs is insufficient. A good connection is achieved between the filler metal and the base metal, and a large amount of Ti/Al brittle IMCs is not found on the interface; this condition is conducive to the improvement of the performance of Ti/Al joint (as shown in Fig. 18). Zhang [83] studied the ultrasonic-assisted high-frequency induction brazing of Ti/Al. Although the Sn element has good spreading and wetting properties, the Sn settles to the bottom layer and its strength is low. The fracture occurs on the Sn-rich phase. The tensile strength of joint is only 51.43 MPa.

In summary, the selection of brazing filler metal is very important. Reasonable selection of solder system, that is, liquid solder wets the base metal and fills the joint gap. At the same time, the multicomponent compounds formed by the diffusion between liquid solder and base metal atoms can inhibit the formation of Ti-Al brittle IMCs, and stable Ti/Al joint can be obtained.

5 Diffusion welding

Diffusion welding realizes the connection of specimens to be welded through the creep and diffusion of the contact surface under the action of certain temperature and pressure. The temperature, time, and pressure are mostly studied in the test.

Song [84] carried out a study on the variation law of vacuum diffusion welding parameters of Ti/Al dissimilar metals. The results show that with the increase in holding
temperature, the microbonding of Ti/Al joint is more compact, and the strength of the joint is increased. However, when the temperature reaches a certain limit value, the strength of the joint decreases with the increase in temperature. The interface of the Ti/Al joint can be smoother by prolonging the holding time. As shown in Figure 19, when the holding temperature is 450 °C and the holding time is 3 h, the Ti/Al joint with continuous interface is obtained, and the maximum tensile strength can reach 152 MPa.

Yao et al. [85] studied the direct diffusion welding of TA2 Ti and L4 Al alloys, and obtained Ti/Al joint with good interface bonding, as shown in Figure 20. The results show that under the condition of 650 °C and 1200 min, the fracture of the joint occurs in the Al alloys, and the tensile strength is only 67 MPa. After a large number of new TiAl3 phases are joined into the weld, the joint strength is close to or even greater than that of Al alloys. Evidently, the formation of Ti-Al IMCs cannot be reduced by direct diffusion welding. Li et al. [86] used Ti with Al coating to realize the vacuum diffusion bonding of Ti/Al dissimilar metals. When the heating temperature is 540 °C–610 °C, the holding time is 45–80 min, the pressure is 5.5–12.4 MPa, and the vacuum degree is (1.86–2.66) × 10⁻⁴ Pa. The thickness of the Ti-Al IMCs is only 3–10 μm, which reduces the adverse effect of brittle IMCs, and no Ti/Al brittle IMCs are found in Al side and Ti side.

Atieh and Khan [87] electroplated Ni on Ti6Al4V Ti alloys to realize the transient liquid phase diffusion bonding between AZ31 Mg and Ti-6Al4V Ti alloys. Under the conditions of 520 °C welding temperature, 20 min holding time, and 0.2 MPa pressure, the maximum tensile strength joint (61 MPa) can be obtained, reaching 50% of the strength of Mg alloys. They found that the bonding mechanism is different at different interfaces. For example, solid diffusion occurs at one side of the Ni-Mg interface, and mutual diffusion of molten state occurs at one side of Ni-Mg interface. To further study the regulatory role of Ni and Cu in the welding of Mg/Ti alloy, Atieh and Khan [88] conducted diffusion bonding between Ti and Mg with dispersed Cu and Ni nanoparticles via electroplated Ni layer on Ti alloys. They found that Cu nanoparticles alone had the best aging effect, and the joint strength reached 69 MPa, which was 15% higher than that of Ni coating only. The microstructure of the joint interface under three different particle modes is shown in Figure 21. The results show that the thickness of interface layer and the types of IMCs are affected by the intervention of different dispersion nanoparticles in the diffusion bonding of Ti/Mg alloy. Mg₂Ni and Mg₃AlNi₂ are formed when Ni particles are added alone. On the contrary, Cu particles can significantly reduce the width of joint zone, and IMCs are formed at the interface to form CuMg₂ and Mg₂Cu₆Al₅.
Qin [89] of Xi’an University of Science and Technology studied Ti/Mg transient liquid phase diffusion bonding using pure Ni foil, Cu foil, and Al foil as interlayer. The results show that the microstructure of Ti/Mg interface has a lamellar distribution with different metal foils. The maximum strength of Ti/Mg joint reaches 71 MPa at 540°C, and the 20-minute fracture analysis shows that the fracture mode is ductile. a-Ti solid solution, Ti₃Al, (α-Mg + Mg₂Al) eutectic structure, and a small amount of Mg₁₇Al₁₂ are formed at the interface from Ti side to Mg side. However, when Ni and Cu foils are used, the joint fracture tends to be brittle. Chen and Ge [90] mainly studied the microstructure and mechanical properties of Ti/Mg transient liquid phase diffusion welding joint in the form of adding Ni foil interlayer. When the welding temperature was 525°C, the holding time was 20 min, and the welding pressure was 0.2 MPa. In addition, the maximum tensile strength of Ti/Mg joint was 57 MPa, and Mg₃Ni and Mg₃AlNi compounds were found at the joint interface.

This study indicates that diffusion welding slightly affects the welding of Ti alloy and other metals. The formation of brittle IMCs can be effectively reduced by adding intermediate layer or Al on the Ti surface and controlling process parameters reasonably. The metal transition layer formed after welding is thinner and the residual stress of joint is lower. However, the tensile strength of the Ti/Al joint obtained by diffusion welding is low. Thus, it is difficult to widely use in high strength occasions.

6 Friction stir welding

Friction stir welding (FSW) is a new high-quality solid-state welding technology, which uses friction heat and plastic deformation heat as welding heat source [91]. It can realize the bonding between atoms of the material to be welded at the temperature below the melting point.

Chen et al. [92] used friction fusion welding spot welding to realize the connection of Ti/Al joints. The results show that the tensile strength of Ti/Al joint reaches 18.2 kN. Al₃Ti is formed at the Ti/Al interface in the process of friction melting spot welding. Vacchi et al. [93] lap welded AA5754 Al alloys and TC4 Ti alloys by friction stir spot welding. The results show that the friction stir spot welding process promotes a large number of microstructure changes along the welded joint, thereby directly reflecting the mechanical properties and corrosion behavior of different welding areas. The corrosion resistance of the stir zone is better than that of the other welding zones (HAZ and base metal) because of the high uniformity and grain refinement of the welding process. Choi et al. [94] performed butt welding of pure Ti and pure Al by FSW. The Al bias side of the pin was welded to reduce the mixing of Ti grains in the fusion zone to suppress the formation of Ti-Al IMCs.
To further inhibit the formation of Ti-Al IMCs, Wu et al. [100] carried out friction stir welding of TC4 Ti and Al6082 Al alloys by adding different thicknesses of filler metal Zn. They obtained Ti/Al joints with different filler metal thicknesses, as shown in Figure 23. When the thickness of Zn is 0.05 mm, the tensile strength (154 MPa) of Ti/Al joint is higher than that of other filler metal Zn thickness. The results show that the IMCs in the weld is AlZn, no Ti-Al IMCs are formed, and the joint presents a mixed fracture mode of brittle and ductile fracture. The results show that the formation of Ti-Al IMCs is inhibited by the addition of filler metal, and the fracture mode of Ti/Al joint changes into mixed fracture, thereby improving the tensile strength of the Ti/Al joint.

Li et al. [101] lap-welded Mg/Ti dissimilar alloys by friction stir lap welding. The stir pin penetrated the bottom Ti alloys during the welding process. When the welding speed decreases from 120 mm/min to 80 mm/min, the fracture position is transferred from the lap interface to the upper Mg alloy. The maximum tensile shear strength of the joint is 424 N/mm. Li et al. [102] studied the generation of friction heat and atomic diffusion behavior in friction welding of Mg/Ti dissimilar alloys. The results show that the friction coefficient mainly goes through two stable stages. The first stable stage corresponds to Coulomb friction. The second stable stage corresponds to the adhesive friction of fully plastic flow. Compared with high-energy beam brazing, the addition of transition metal layer in FSW can also inhibit the formation of brittle IMCs.

To obtain dissimilar friction stir welding joint of Ti and Mg, Choi et al. [103] inserted Al foil between Ti and Mg. The thickness of Al foil, probe offset, and welding speed were optimized, and the Ti/Mg joint with good performance was obtained (Fig. 24). With the increase in Al foil thickness, the size and quantity of welding defects in the Mg stir zone increase due to poor material flow. The fracture of joint in the heat affected zone of Mg alloys is due to the formation of thin IMC layer at the welding interface and inhibition of Ti–Mg brittle IMC formation in the Mg stirring zone.

Choi et al. [104] optimized the dissimilar friction stir welding of incoherent pure Ti/Mg by adjusting the welding speed with Al filler material of 0.05 mm thickness. At lower welding speed, the average grain diameter in the stirring zone of Ti/Mg joint decreases. The reason is that the concentration of Al dissolved in Mg matrix increases at lower welding speed, which promotes the occurrence of dynamic recrystallization in the friction stir process.

Ji et al. [105] welded Ti/Mg dissimilar alloy by friction
stir lap (Mg on top), and the maximum tensile strength of Ti/Mg joint was 424 N/mm. When the welding speed decreased from 120 mm/min to 80 mm/min, the fracture position transferred from the lap interface to the upper Mg alloys. Song et al. [106] welded TC4 Ti and AZ31B Mg alloys by friction stir welding. They found that when the stirring needle is inclined to Mg side, the Ti grains mixed into the fusion zone decrease, the grains in the joint are reduced, and the strength is increased. This research indicates that friction stir welding can obtain a certain strength of Ti alloy and other dissimilar metal joints, but with poor flexibility. In addition, heat input is difficult to control and unsuitable for fine machining. In addition, the microstructure and composition of FSW joints are nonuniform, and porosity defects easily appear, thereby limiting the improvement of the mechanical properties of joints.

7 Explosive welding

Explosive welding can produce solid Ti/Al composite plate. A large amount of explosive results in a more refined interface structure, but the microstructure layer also becomes uneven [107]. Annealing treatment, which is also a common method, causes some metal phases to grow continuously, metal phases form metallurgical bonding between metals to improve joint strength. Fronczek et al. [108–111] comprehensively studied the preparation of Ti/Al composites by explosive welding. They studied the microstructure evolution of Ti/Al welding interface at 825 K and different annealing time. The weld is composed of TiAl₃, TiAl₂, TiAl, and Ti₃Al phases after explosive welding, forming fine peninsular structure, as shown in Figure 25. No defects, such as cracks and pores, are found in the fusion zone. Ti/Al joint with good interface bonding is obtained using the impact effect of explosive welding. Abnormal grain growth is observed in Al due to secondary recrystallization, and deformation twins are annihilated in the Ti alloys. The annealing process mainly promotes the growth and development of TiAl₃ IMCs, thereby forming continuous Ti-Al IMCs.

Paul et al. [112] studied the explosive welding of multilayer Ti/Al dissimilar metals and successfully prepared defect-free multilayer composites. The results show that the interface between the two parent metals is wavy or flat, and the solidified melt inclusions are preferentially located in the wave crest and wave vortex. The results show that the wavy interface is always formed in the layered structure near the explosive charge.

![Fig. 23. Micro morphology of joint edge area with different filler metal thickness: (a) 0 mm; (b) 0.02 mm; (c) 0.05 mm; (d) 0.1 mm (Reproduced with permission from Ref. [100] Copyright 2019 CNKI).](image)
Lazurenko et al. [113] produced 40 layers of Ti/Al composites by one shot explosive welding. The structure of the composite was studied by SEM and TEM. The mixed zone structure is produced at the interface in the process of explosive welding. The complex process of mixing and rapid solidification in these regions leads to the formation of different stable structures. Local melting and rapid solidification of eddy current directly lead to the formation of Al3Ti and stable phase IMCs during explosive welding. Figure 26 shows a large number of refined Al and Ti grains, which greatly improve the strength of Ti/Al joints.

Boronski et al. [114] compared and analyzed the fracture toughness of explosive welded Al/Ti composites and introduced the environmental temperature and low temperature conditions. They found that the characteristic of layered materials at low temperature is crack resistance. Fang et al. [115] found a smooth and well-connected interface by explosive welding of Ti/Al plate. Deformation and fracture mainly occur in the Al layer. However, the Ti layer under vertical loading, Al layer, and the interface play a role in parallel loading. The rate sensitivity of this Ti/Al alloy is consistent with that of the constituent metals. A single deformation band appears in the Al layer under quasistatic loading under the condition of vertical loading, and multiple deformation bands appear simultaneously under dynamic loading. Guo Xunzhong et al. [116,117] prepared Ti-Al-Ti layered composite materials by explosive composite method with pure Ti plate and pure Al plate. Then, they further processed the Ti/Al/Ti layered composite material by heat treatment and hot pressing process. The results show that the interface of the composite plate is mainly wavy interface and straight. The interface has good bonding performance and can withstand the subsequent large secondary plastic deformation. Figure 27 shows that the Al layer fully reacts after heat treatment for 25 h and hot pressing for 2.5 h. The diffusion reaction layer is mainly composed of TiAl3 and Ti2Al5 phases. Fang et al. [118] carried out theoretical analysis and experimental research on the explosive welding manufacturing process of Ti/Al composite plate. They found that the interface of Ti/Al composite plate is wavy, and the diffusion of metal elements occurs near the interface and in the melting layer.

Zhao et al. [119] prepared Ti/Al/Mg laminated composite plates by explosive welding with thin Al alloy plates as the transition layers. The interface of Al/Mg and Al/Mg was melted. The results showed that the Ti/Al interface was a small-scale wave, whereas the Al/Mg interface is a large-scale wave. The composite plate broke along the Al/Mg interface.

Wu [120] studied the explosive welding of Ti/Mg. The author prepared Ti/Mg and Mg/Al/Ti composite plates by explosive welding. The interface analysis of the Ti/Mg composite plate shows that severe plastic deformation occurred on the Mg and the Ti side, and adiabatic band was found on the Mg alloys. The analysis of the interface of Mg/Al/Ti composite plate shows that element diffusion occurred at the interface of Al/Mg and Ti/Al, thereby indicating that the Al element has a certain adjustment effect on the interface.

Although explosive welding can effectively solve the problem of poor weldability of Ti and other metals, realizing explosive bonding of ultrathin Ti plate and other metal plates at present is difficult; thus, further research is required. Although explosive welding does not inhibit the formation of Ti-based IMCs, the characteristics of high impact force refine the grains at the interface, and high strength dissimilar metal joints are obtained. Strength and plasticity can satisfy the requirements of industrial production.

Fig. 24. Cross sections observed at different foil thicknesses (a) 0.05 mm, (b) 0.2 mm, (c) 0.5 mm and (d) 1.0 mm (Reproduced with permission from Ref. [103] Copyright 2019 Elsevier).

Fig. 25. SEM image and Al element distribution of Ti/Al interface in explosive welding sample (Reproduced with permission from Ref. [108] Copyright 2016 Elsevier).
8 Conclusions

The poor weldability between Ti alloys and other alloys is mainly due to the great difference in their physical and chemical properties. Brittle Ti-based IMCs are easily formed in the weld, leading to the decrease in joint strength. The content of Ti-based IMCs in dissimilar metal joints can be reduced by heat source migration. However, its formation cannot be avoided. The addition of intermediate layer can not only reduce the content of IMCs, but can also form better plastic compounds, which greatly reduce the brittleness of dissimilar metal joints.

The content of Ti-based brittle IMCs in dissimilar metal joints can also be greatly reduced by means of fusion brazing, and the content can be limited to a specific area. In addition, the effective connection of Ti and other alloys can be realized by brazing and diffusion welding. In the brazing process of Ti and other alloys, the interface can be wetted by placing filler metals. The results show that the filler can improve the bonding strength by adjusting the temperature and holding time. The filler of Ni, Al and Cu can be used in Ti/Mg dissimilar metals welding, and the filler of Cu, Al-Si can be used in Ti/Al dissimilar metals welding. The use of filler improves the strength of the joints, through reducing the fusion rate of the base metals in the weld or by shifting the heat source to realize the diffusion connection between the filler and the materials on both sides.

FSW can also inhibit the formation of Ti-based brittle IMCs in dissimilar metal joints by adding interlayer, thereby obtaining dissimilar metal joints with good properties. However, due to the shape of the weldment, its application is limited. Although explosive welding cannot inhibit the formation of Ti-based IMCs, it uses instantaneous high-temperature and high-pressure explosives to firmly combine Ti and other alloys. The purpose of improving the strength of dissimilar metal joints is realized by refining the metal particles in the interface.

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