

Cite this article as: Ma Xianglong, Cao Rui, Dong Hao, et al. Interface Characteristics and Mechanical Properties of TC4 Titanium Alloy and Al6061 Aluminum Alloy Joint Prepared by Hot Isostatic Pressing Diffusion Bonding[J]. Rare Metal Materials and Engineering, 2024, 53(04): 1002-1010. DOI: 10.12442/j.issn.1002-185X.E20230024.

ARTICLE

Interface Characteristics and Mechanical Properties of TC4 Titanium Alloy and Al6061 Aluminum Alloy Joint Prepared by Hot Isostatic Pressing Diffusion Bonding

Ma Xianglong¹, Cao Rui¹, Dong Hao², Wang Tiejun², Yan Yingjie¹

¹ State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals, Lanzhou University of Technology, Lanzhou 730050, China; ² Advanced Technology & Materials Co., Ltd, Beijing 100081, China

Abstract: Hot isostatic pressure diffusion bonding experiments were conducted on the dissimilar alloys of TC4 titanium alloy and Al6061 aluminum alloy. The interface characteristics, formation mechanism, and mechanical properties of the TC4/Al6061 joint were investigated, and the relevant experiment phenomena were explained by thermodynamic analysis. Results show that obvious mutual diffusion of elements occurs on both sides of base material after hot isostatic pressure diffusion bonding and subsequent annealing treatment. The chemical potential driving force leads to the enrichment of Si and Mg elements in the diffusion transition zone and Al side interface, respectively. The intermetallic compounds, including TiAl₃, TiAl, and Ti₃Al, are formed through metallurgical reactions at the joint interface. The calculation results through effective heat formation model indicate the preferential formation of TiAl₃ phase. The hardness test indicates that the Ti-Al intermetallic compounds formed at the interface exhibit higher hardness. The tensile test reveals that the maximum tensile strength of joint reaches 144 MPa.

Key words: TC4 titanium alloy; Al6061 aluminum alloy; hot isostatic pressure diffusion joining; interface characteristic; mechanical property

Heterogeneous metal joining components attract much attention due to their combined advantages of two metals, which can usually satisfy the requirements with low cost. Titanium and its alloys have high specific strength and good corrosion resistance, and thereby are widely used in the aerospace and transportation industries. However, the high production cost restricts their further application^[1-2]. Aluminum and its alloys have good electrical and thermal conductivity, low density, and corrosion resistance, and are widely used in the manufacture of new energy vehicles and aircraft parts^[3-4]. Titanium/aluminum composite possesses combined advantages of both alloys, which can simultaneously satisfy the requirements of high strength and lightweight and greatly reduce cost, therefore presenting great potential in application. However, the preparation of such metallurgically well-bonded composite faces many challenges.

Recently, the titanium/aluminum hetero-metallic joining has

been widely researched. However, there is a huge difference in the physical properties between titanium and aluminum. The melting point of titanium is 1668 °C, which is higher than that of aluminum (1008 °C). The linear expansion coefficient of aluminum is nearly three times larger than that of titanium. The thermal conductivity difference of titanium and aluminum alloys is nearly 204.8 W·m⁻¹·K⁻¹. Besides, metallurgical reactions are prone to occur during the titanium/aluminum joining process, resulting in the formation of brittle Ti-Al intermetallic compounds which cause uneven distribution and aggregation at the joint, and therefore leading to the degradation of joint performance^[5-7]. Direct fusion welding of titanium/aluminum hetero-metals can easily produce defects, such as cracks and pores, in the welding heat-affected zone, which reduces the joining performance of joint^[6-8]. It is found that the pressure welding method can achieve good metallurgical bonding for titanium/aluminum hetero-

Received date: August 15, 2023

Foundation item: National Natural Science Foundation of China (52175325)

Corresponding author: Cao Rui, Ph. D., Professor, State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals, Lanzhou University of Technology, Lanzhou 730050, P. R. China, E-mail: caorui@lut.edu.cn

Copyright © 2024, Northwest Institute for Nonferrous Metal Research. Published by Science Press. All rights reserved.

metals^[9-11]. Liu et al^[12] joined AA6063 alloy with Ti6Al4V alloy by isothermal compression diffusion and found that the interface is well formed and a diffusion layer with certain thickness is formed at the joint interface. The diffusion layer is mainly composed of TiAl₃ phase and titanium-aluminum solid solution. Kar et al^[13] joined Al20204 and Ti6Al4V alloys by friction stir welding and reported that the continuous plastic deformation without defects occurs at the joint interface. Fine Ti particles are formed at the Ti side, and more dynamic recrystallization grains are produced at the Al side. The maximum tensile strength of the joint reaches 277 MPa. Guo et al^[14] prepared Ti/Al/Ti composite materials by explosive welding and found that titanium and aluminum elements undergo mutual diffusion, the interface bonding performance is excellent, and a diffusion reaction layer including TiAl₃ and Ti₂Al₃ phases is formed at the interface. These results show that the pressure welding with low heat input can avoid defects, such as cracks, in the fusion welding heat-affected zone, the interface is well formed, and high-quality metallurgical bonding of titanium/aluminum can be achieved.

Hot isostatic pressing (HIP) technique, namely diffusion welding, involves the pressure and heating treatments onto the components in a protective atmosphere for a certain period, and then the components are joined through plastic deformation and diffusion reactions. HIP diffusion-bonded components have the characteristics of high density and good metallurgical bonding, especially for the joints containing heterogeneous metal components with many welding positions. HIP technique can be conducted at special positions where traditional welding methods cannot. It can also join multiple heterogeneous metal components at the same time, and the quality of the joining interface is superb, which greatly improves the production efficiency^[15-16]. Currently, HIP diffusion bonding is a feasible and commonly used technique for manufacture of new composite materials in the field of heterogeneous metal joints. The joints of titanium/aluminum dissimilar metal components are mostly special-shaped parts in practical applications. In the joining processes of special-shaped parts, high-quality all-position welded joints can hardly be obtained by the traditional pressure welding method. The joining of special-shaped parts with stable joining quality can be achieved by HIP diffusion joining. However, HIP diffusion bonding for titanium/aluminum hetero-metals is rarely researched, and the microstructure, mechanical properties, and formation mechanism of HIP diffusion-bonded interface of titanium and aluminum hetero-metals are still obscure.

Therefore, in this research, the feasibility of HIP diffusion bonding to join TC4 titanium alloy and Al6061 aluminum alloy was investigated. The formation mechanism,

microstructure, and mechanical properties of the joints were studied. The formation order of intermetallic compounds at the interface was predicted by effective thermal model and verified by experiment results. This research provided theoretical and experimental basis for the development of HIP diffusion bonding of TC4 titanium alloy and Al6061 aluminum alloy, which was conducive to the high-strength and high-efficiency connection between titanium/aluminum hetero-metals.

1 Experiment

The chemical composition of TC4 titanium alloy and Al6061 aluminum alloy used in the experiments is shown in Table 1. The phase composition was analyzed by micro-area X-ray diffraction (XRD). Fig.1 shows the microstructures and XRD patterns of the base materials. TC4 titanium alloy was annealed for analysis. According to XRD pattern in Fig. 1c, TC4 base material has fine and uniform microstructure and it is mainly composed of equiaxed α -Ti phase and gray-white β -Ti phase. As shown in Fig.1b and 1d, the Al6061 aluminum alloy is mainly composed of flaky Mg₂Si phase and Al-based solid solution.

Several specimens of TC4 titanium alloy and Al6061 aluminum alloy with diameter of 20 mm and height of 35 mm were prepared for experiments. To achieve better diffusion bonding, Al6068 aluminum alloy tube with inner diameter of 20 mm, outer diameter of 25 mm, and height of 75 mm was used as the metal can. Before HIP diffusion bonding, the joining surfaces of all specimens were sequentially polished by 300# – 2000# sandpaper to achieve smooth and flat interface. The specimens were then ultrasonically cleaned in acetone solution for 5 min to remove oil stains and wiped by alcohol using non-woven cloth. HIP diffusion bonding was conducted by the HIPEX400 HIP diffusion bonding furnace. Based on the commonly used temperature range for diffusion welding, such as $0.6T_m - 0.8T_m$ (T_m is the lowest melting point of base material), and combined with experiment results, the experiment parameters of HIP diffusion bonding process were set as follows: temperature of 530–540 °C, pressure of 140 MPa, and holding time of 3 h. To eliminate the influence of residual stress, the specimens were subjected to post-weld heat treatment (PWHT) at 500 °C for 24 h^[17-18]. The temperature variation of HIP diffusion bonding and PWHT processes is shown in Fig.2.

After stress-release annealing of the joints after HIP diffusion bonding, the specimens were sampled and mechanically polished by 300#–2000# sandpaper. The TC4 titanium alloy side was corroded by the solution of 2vol% HF+4vol% HNO₃+94vol% H₂O, and the Al6061 aluminum alloy side was corroded by Weck reagent (100 mL water+4 g

Table 1 Chemical composition of base materials (wt%)

Material	Si	Mg	Fe	Cr	V	Ti	Al
TC4	-	-	0.30	-	3.5–4.5	Bal.	5.5–6.75
Al6061	0.4–0.8	0.8–1.2	<0.7	0.04–0.35	-	<0.15	Bal.

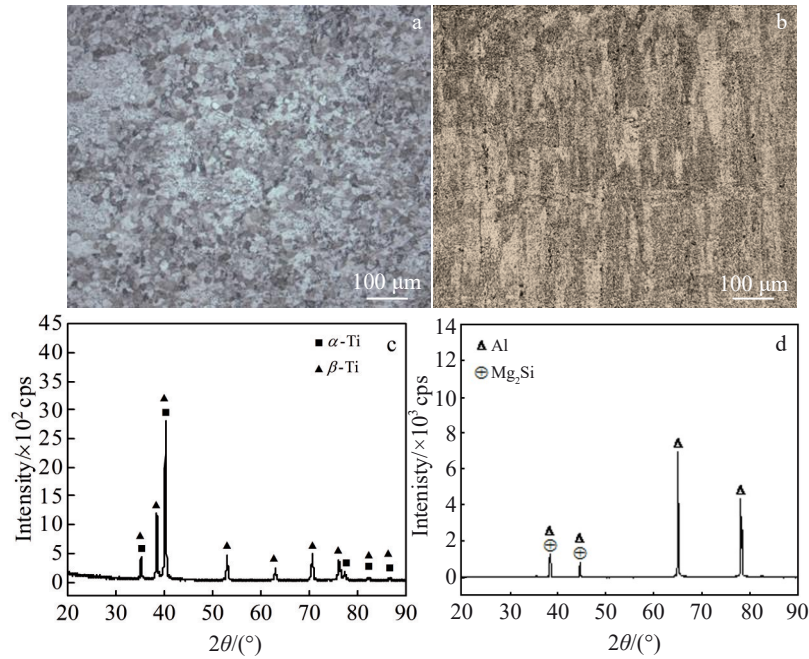


Fig.1 Microstructures (a–b) and XRD patterns (c–d) of annealed TC4 alloy (a, c) and Al6061 alloy (b, d)

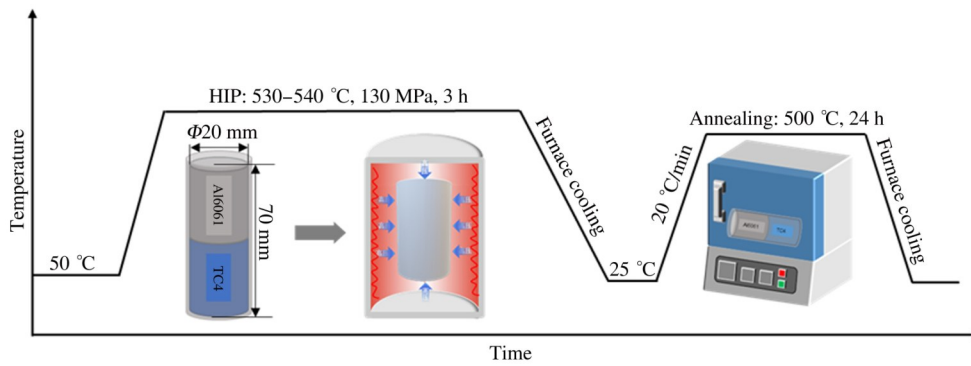


Fig.2 Temperature variation of HIP diffusion bonding and PWHT processes

potassium permanganate+1 g sodium hydroxide). The microstructure of the joint interface was observed by Zeiss Axio Observer optical microscope (OM) and JEOL JSM 7200F scanning electron microscope (SEM). The Oxford X-Max energy dispersive spectrometer (EDS) was used to analyze the diffusion behavior of interface elements on the joint interface area. The hardness test was performed by VH1102-01-0087 Vickers hardness tester. The area near the joint boundary of $500\ \mu\text{m}\times 700\ \mu\text{m}$ was selected and divided into small grids with dimension of $100\ \mu\text{m}\times 100\ \mu\text{m}$, column spacing of 0.15 mm, and row spacing of 0.2 mm. The load was 0.98 N and the hardness distribution cloud map of the joint was obtained. The room temperature tensile test was performed by Instron 5582 dual-column electronic universal testing machine. The fracture surface of the specimens was observed by SEM and the phase was characterized by XRD.

Thermodynamic analysis of binary alloy systems was used to analyze the diffusion behavior of elements by calculating the formation enthalpy, Gibbs free energy, and chemical

potential of the system using the Miedema model^[19]. The actual heat of formation reaction can be calculated by the effective heat formation (EHF) model to predict the formation order of compound phases in the binary systems^[20]. Currently, the Miedema model and EHF model are widely used in the welding field^[21–23].

2 Results and Discussion

2.1 TC4/Al6061 interface characteristics of joints prepared by HIP diffusion bonding

Fig. 3 shows OM and SEM backscattered images of the TC4/Al6061 joints prepared by HIP diffusion bonding. No obvious cracks or voids can be observed at the bonding interface in Fig.3a. Fig.3b shows the formation of the reaction layer with a certain thickness, which further demonstrates the good metallurgical bonding of the joint.

Fig. 4 shows the microstructures and EDS element distributions of the TC4/Al6061 joint prepared by HIP

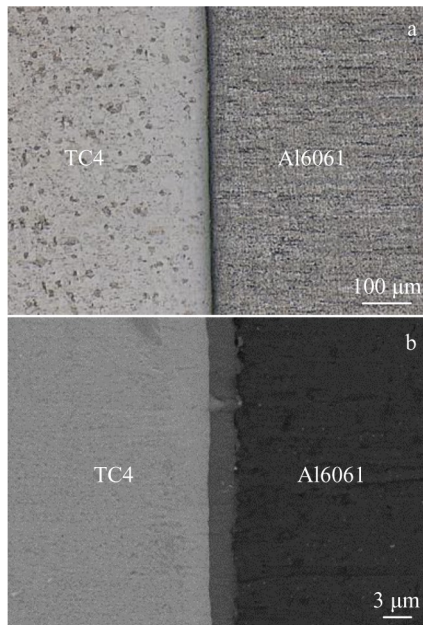


Fig.3 OM image (a) and SEM backscattered image (b) of TC4/Al6061 joint prepared by HIP diffusion bonding

diffusion bonding. Fig. 4a shows that the diffusion transition zone exists in the middle area of TC4/Al6061 joint. The joining interface between TC4 substrate and diffusion transition zone is almost straight, whereas that between Al6061 substrate and diffusion transition zone is wavy. This phenomenon is attributed to the plastic deformation difference caused by the hardness difference between the two substrates during the diffusion bonding process. Compared with the TC4 substrate, the Al6061 substrate is softer and has a greater degree of plastic deformation. Fig. 4b is the magnified image of Fig. 4a, and the thickness of the diffusion transition zone is

about 2 μm. Fig. 4c–4f show the EDS surface scanning results of the TC4/Al6061 joint in Fig. 3b. It can be seen that obvious Si segregation exists in the diffusion transition zone, and the Mg segregation occurs at the interface of Al6061 side. This phenomenon is similar to the results in Ref. [12,24]. Additionally, the interface consists of TiAl₃ phase (0.2 μm), TiAl phase (2 μm), and Ti₃Al phase (0.5 μm). The reasons for the segregation of Si and Mg elements are as follows. (1) During the diffusion bonding process, Al, Si, and Mg atoms on the Al6061 substrate side diffuse to the TC4 substrate side. Because the atomic radii of Al (0.117 nm) and Si (0.143 nm) elements are smaller than that of Mg (0.162 nm), the activation energy for the diffusion of Si and Al atoms is lower than that for Mg atoms, therefore resulting in easier diffusion of Si and Al atoms. (2) The chemical formation enthalpies of Si and Ti are negative, indicating that they can spontaneously generate strong chemical interactions, which provide driving force for the Si diffusion. The Si and Al atoms diffusing to the TC4 substrate side occupy most diffusion channels, and thus the diffusion of Mg atoms is relatively inhibited. In addition, the Al6061 substrate side provides a large number of vacancies for the remaining Mg atoms^[12]. (3) The chemical potential of Si in the diffusion transition zone is decreased with increasing the Ti atoms, and the chemical potential gradient of Si is large.

Fig. 5 shows EDS line scanning results of the TC4/Al6061 joint in Fig. 4a. Table 2 shows EDS point scanning results at different positions of the TC4/Al6061 joint in Fig. 4b. Obviously, mutual diffusion occurs on both substrate sides and the Ti-Al intermetallic compounds with different thicknesses are formed at the joint interface by metallurgical reactions. Based on the point scanning results in Table 2 and XRD patterns in Fig. 6, it can be determined that the joint is composed of the Ti₃Al, TiAl, and TiAl₃ phases. The Ti₃Al

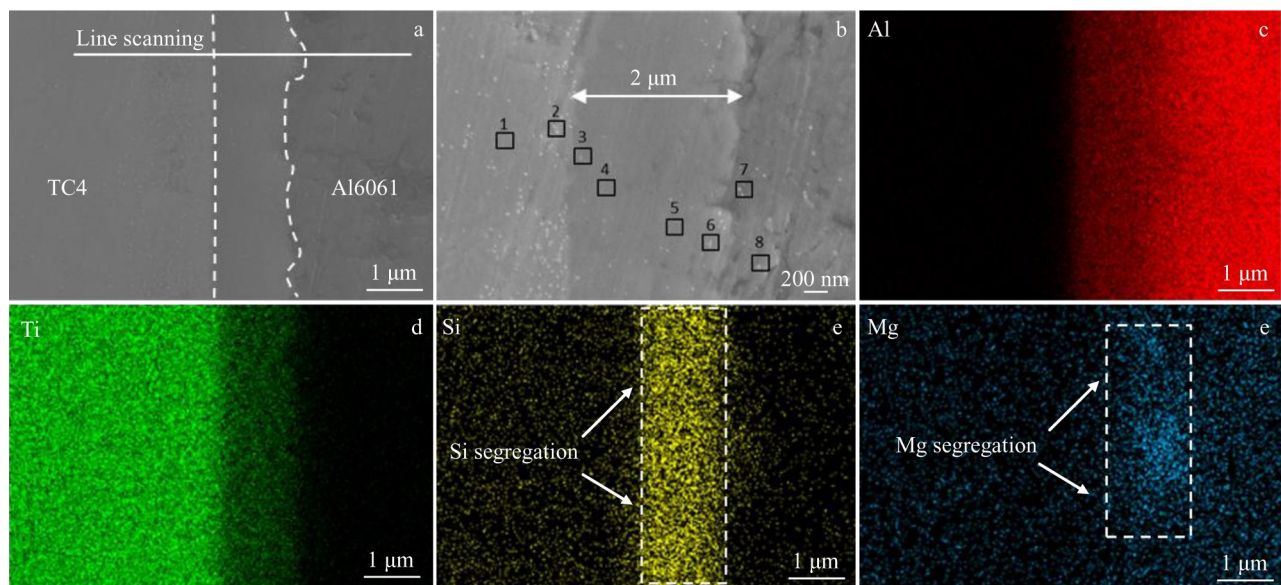


Fig.4 Microstructure of TC4/Al6061 joint prepared by HIP diffusion bonding (a); magnified image of Fig. 4a (b); EDS element distributions of Fig. 3b: (c) Al element, (d) Ti element, (e) Si element, and (f) Mg element

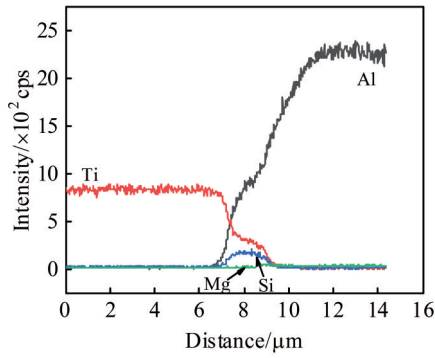


Fig.5 EDS line scanning results of TC4/Al6061 joint in Fig.4a

Table 2 EDS point scanning results at different positions of TC4/Al6061 joint in Fig.4b

Point	Content/wt%					Possible phase
	Al	Ti	Si	Mg	Fe	
1	1.5	97.8	0.31	-	0.39	TC4
2	26.24	69.58	3.97	0.20	0.01	Ti ₃ Al
3	44.14	47.01	8.85	-	-	TiAl
4	48.41	42.39	9.02	0.18	-	TiAl
5	44.10	49.59	5.97	0.35	-	TiAl
6	49.13	43.83	6.10	0.38	0.56	TiAl
7	57.87	34.38	6.31	0.83	0.61	TiAl ₃
8	66.79	27.94	3.23	1.46	0.58	TiAl ₃

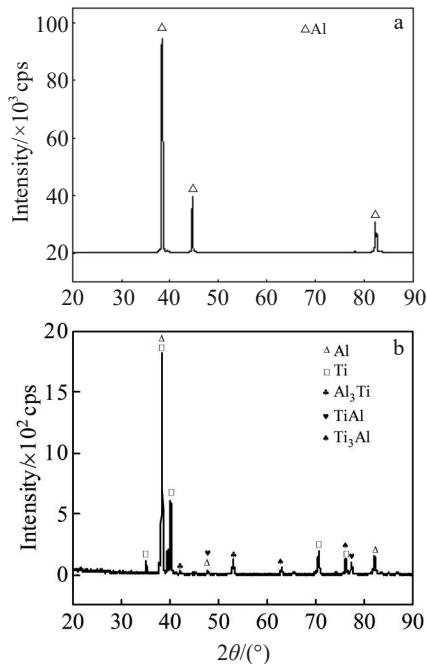


Fig.6 XRD patterns of tensile fracture surfaces of TC4/Al6061 joint at Al6061 substrate side (a) and at TC4 substrate side (b)

phase (about 0.2 μm in thickness) is located at the interface of Ti substrate side, the TiAl phase (about 2 μm in thickness) is located in the diffusion transition zone, and the TiAl₃ phase

(about 0.5 μm in thickness) is located at the interface of Al6061 substrate side. These results are consistent with those in Ref.[22–23].

2.2 Thermodynamic analysis of TC4/Al6061 joint prepared by HIP diffusion bonding

The diffusion behavior of elements is often influenced by the chemical potential gradient. Driven by the chemical potential gradient, elements always diffuse from the region with high chemical potential to the region with low chemical potential^[24–25]. The chemical potential of substance is also the partial molar free energy, which can be calculated by Eq.(1), as follows:

$$\Delta\mu_i = \frac{\partial G}{\partial x_{ij}} \quad (1)$$

where μ_i is the chemical potential of component i ; G is the free energy of system; x_{ij} is the mole fraction of component i or j .

According to the Miedema model, the calculation equations of free energy of system G are as follows:

$$G = G^1 + G^E \quad (2)$$

$$G^1 = x_i G_i + x_j G_j + RT(x_i \ln x_i + x_j \ln x_j) \quad (3)$$

$$G^E = \Delta H_{ij} \left[1 - T \left(\frac{1}{T_{m,i}} + \frac{1}{T_{m,j}} \right) / 14 \right] \quad (4)$$

$$\Delta H_{ij} = f_{ij} \frac{x_i [1 + \mu_i x_i (\varphi_i - \varphi_j)] x_j [1 + \mu_j x_j (\varphi_j - \varphi_i)]}{x_i V_i^{2/3} [1 + \mu_i x_j (\varphi_i - \varphi_j)] + x_j V_j^{2/3} [1 + \mu_j x_i (\varphi_j - \varphi_i)]} \quad (5)$$

$$f_{ij} = \frac{2pV_i^{2/3}V_j^{2/3} [q/p(\Delta n_{ws}^{1/3})^2 - (\Delta\varphi)^2 - a(r/p)]}{(\Delta n_{ws}^{1/3})_i^{-1} + (\Delta n_{ws}^{1/3})_j^{-1}} \quad (6)$$

where x is the mole fraction of component; R is the gas constant as 8.324 J/(mol·K)⁻¹; T is the thermodynamic temperature; T_m is the melting point of component; φ is the electronegativity of component; V is the molar volume of the component; n_{ws} is the electron density of component; q , r , μ , and a are empirical constants.

Based on the Miedema model and relevant thermodynamic parameters^[26–28], the relationship between the Ti and Si contents and the Si chemical potential at 530–540 °C is calculated according to Eq.(1–6), and the results are shown in Fig.7. It can be seen that at 530–540 °C, when $x_{Ti} < 0.5\text{mol}\%$, the chemical potential of Si is decreased with increasing the Ti content. When $x_{Ti} > 0.5\text{mol}\%$, the chemical potential of Si is increased with increasing the Ti content. According to EDS point scanning results of the joint at different positions in Table 2, the Ti content in the diffusion transition zone is less than 0.5mol%. Therefore, during HIP diffusion bonding of the TC4/Al6061 dissimilar metals, the chemical potential of Si is decreased with increasing the Ti content, which causes the Si atoms on the Al side to continuously accumulate towards the diffusion transition zone and finally results in the Si segregation phenomenon.

Based on EDS point scanning result in Table 2 and XRD results of the fracture surfaces in Fig. 6, Ti-Al intermetallic compounds are formed at the interface of TC4/Al6061 joint prepared by HIP diffusion bonding. The formation of these intermetallic compounds has an important influence on the

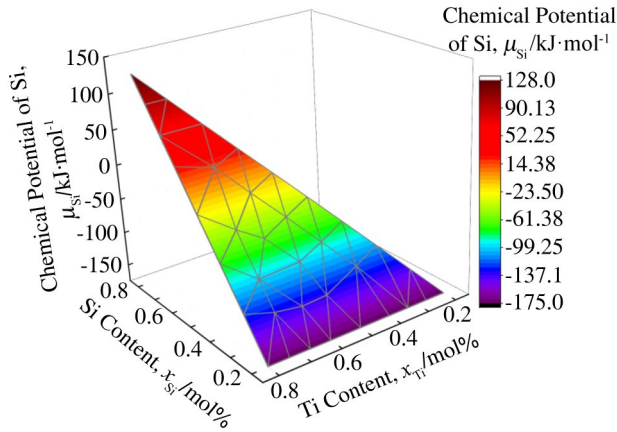


Fig.7 Relationship between Ti and Si contents and chemical potential of Ti-Si binary system at 530–540 °C

joint properties. Therefore, the formation sequence of Ti-Al intermetallic compounds in the Ti-Al binary system should be predicted. Based on the relevant thermodynamic data of the alloy system, Pretorius et al.^[20-29] proposed an EHF model and successfully applied it to the formation sequence of Cr-Si binary compounds. Laik et al.^[30] also predicted the compound formation sequence in the Zr-Al binary system by this model. According to EHF model, for the Ti-Al binary system, the eutectic composition with the lowest eutectic temperature (660.45 °C) in the Ti-Al binary phase diagram is selected as the effective composition, namely 98.0Al-2.0Ti (at%) alloy, with Ti as the control element^[31]. EHF of Ti-Al intermetallic compounds at different temperatures can be expressed, as follows:

$$\Delta G_f^\circ(T) = \frac{c_c}{c_0} \Delta G_f(T) \quad (7)$$

$$\Delta G_f(TiAl_3) = (-40\,349.6 + 10.365\,25T) \times 10^{-3} \quad (8)$$

$$\Delta G_f(TiAl) = (-37\,445.1 + 16.793\,76T) \times 10^{-3} \quad (9)$$

$$\Delta G_f(Ti_3Al) = (-29\,633.6 + 6.708\,01T) \times 10^{-3} \quad (10)$$

where $\Delta G_f^\circ(T)$ is the effective heat of formation energy at different temperatures T with unit of $\text{kJ} \cdot (\text{mol} \cdot \text{at}\%)^{-1}$; $\Delta G_f(T)$ is the molar reaction standard heat of formation at different temperatures T with unit of $\text{kJ} \cdot (\text{mol} \cdot \text{at}\%)^{-1}$; c_c is the effective concentration of Ti with unit of at%; c_0 is the concentration of Ti in the Ti-Al compound with unit of at%.

The molar reaction standard heats of formation $\Delta G_f(T)$ of $TiAl_3$, $TiAl$, and Ti_3Al intermetallic compounds at different temperatures T can be calculated by Eq.(8–10)^[32], respectively. Therefore, the effective heats of formation energy of Ti-Al intermetallic compounds at 427–627 °C are calculated, as shown in Fig.8.

As shown in Fig.8, it can be seen that $TiAl_3$ has the lowest effective heat of formation energy at 530–540 °C, and it is firstly generated at the interface, followed by the $TiAl$ and Ti_3Al phases. These results are consistent with the experiment results. This prediction result is also consistent with the results in Ref.[28,32].

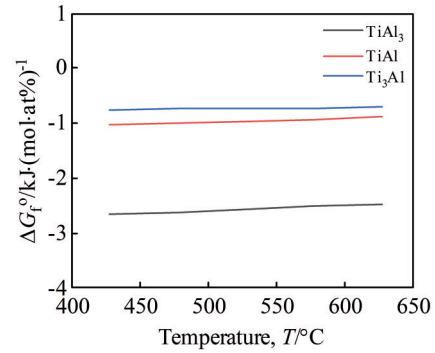


Fig.8 Effective heats of formation energy of Ti-Al intermetallic compounds at 427–627 °C

2.3 Formation mechanism of TC4/Al6061 joint prepared by HIP diffusion bonding

Fig.9 shows the formation mechanism of the TC4/Al6061 joint prepared by HIP diffusion bonding, which can be divided into three stages.

In the first stage, the yield strength of TC4 and Al6061 alloys is decreased with increasing the temperature. At the interface between TC4 and Al6061 alloys, the isostatic pressure causes plastic deformation, promoting the complete physical contact between TC4 and Al6061 alloys, as shown in Fig.9a. Subsequently, during HIP diffusion bonding process, due to the concentration gradient of elements in TC4 and Al6061 alloys, Ti atoms in TC4 mainly diffuse towards the Al6061 side, whereas Al, Si, and Mg atoms in Al6061 alloy mainly diffuse towards the TC4 side. The increase in temperature and pressure promotes the element diffusion. Based on the thermodynamic analysis, $TiAl_3$ has the lowest effective heat of formation energy. Therefore, Ti and Al atoms firstly undergo metallurgical reactions to form the $TiAl_3$ phase, as shown in Fig.9b. In the third stage, due to the asymmetric diffusion of Ti and Al atoms, at the same temperature, the diffusion of Ti atoms towards the Al side is stronger than that of Al atoms towards the Ti side below the melting point of Al^[33]. Therefore, the $TiAl_3$ phase grows on the $TiAl_3$ /Al side, and Si and Mg atoms are enriched in the diffusion transition zone and Al side interface, respectively, which is driven by the chemical potential gradient, as shown in Fig.9c. After long-term PWHT annealing, metallurgical reactions ($Ti+3Al=TiAl_3$, $2Ti+TiAl_3=3TiAl$, $3Ti+Al \rightarrow Ti_3Al$) occur in the joint^[33], forming Ti_3Al , $TiAl$, and $TiAl_3$ layers with a certain thickness, as shown in Fig.9d.

2.4 Mechanical properties of TC4/Al6061 joint prepared by HIP diffusion bonding

Fig.10 shows the hardness distribution of the TC4/Al6061 joint prepared by HIP diffusion bonding. It can be seen that on the TC4 titanium alloy interface side, the average hardness value ($HV_{0.1}$) near the interface is the highest of 1920.8 MPa. The average hardness value slightly decreases to 1784.4 MPa away from the joint interface. On the Al6061 aluminum alloy side, the average hardness value near the interface is the highest, reaching 1127.0 MPa. The average hardness value

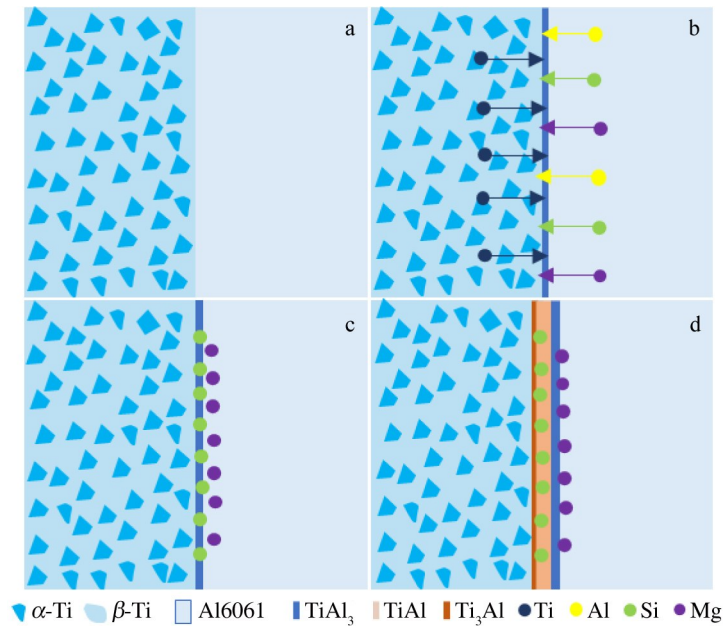


Fig.9 Formation mechanism of TC4/Al6061 joint prepared by HIP diffusion bonding: (a) the first stage; (b) the second stage; (c) the third stage; (d) after annealing

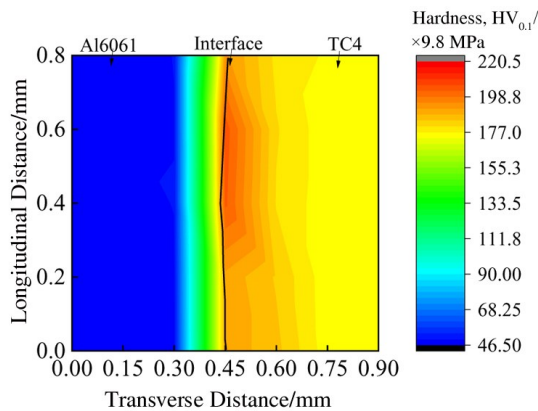


Fig.10 Hardness distribution of TC4/Al6061 joint prepared by HIP diffusion bonding

rapidly decreases and finally reaches a stable average hardness value of 470.4 MPa away from the joint interface, which decreases by 58.26%, compared with that of the joint interface at Al6061 aluminum alloy side. The change in the joint hardness is related to the diffusion layer at the interface, where Ti-Al intermetallic compounds are formed due to atomic diffusion and metallurgical reactions. Therefore, the hardness of formed intermetallic compounds is higher than that of the substrate materials^[12,24]. The further the distance away from the diffusion layer, the less intense the atomic diffusion in the two substrate materials. Thus, less Ti-Al intermetallic compounds are formed, which results in the decrease in the average hardness.

The stress-strain curves of TC4/Al6061 joint during the tension tests are shown in Fig. 11. The brittle fracture is the dominant fracture type of tensile fracture surface. The maximum tensile strength of the joint reaches 144 MPa,

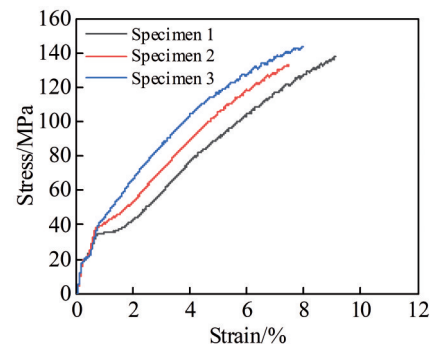


Fig.11 Stress-strain curves of TC4/Al6061 joints during tensile tests

which is higher than that of other diffusion-bonded Ti/Al joints^[33-34]. The thin Ti-Al intermetallic compound layer is well bonded to the substrates, indicating that the TC4/Al6061 joint prepared by HIP diffusion bonding has good metallurgical bonding effect. XRD patterns of the tensile fracture surfaces are shown in Fig. 6, indicating that Ti, Al, TiAl, TiAl₃, and Ti₃Al phases exist in the TC4 substrate side. Only Al diffraction peaks exist in the fracture surface at Al6061 substrate side. Therefore, it can be concluded that the TC4/Al6061 joint fractures in the diffusion layer at the Al6061 substrate side or in the interior of the Al6061 substrate side. The tensile fracture morphologies are shown in Fig. 12. Cleavage fracture with a lot of river patterns appears on the fracture surface of TC4 substrate side. Fig. 12c shows the magnified image of the rectangular area in Fig. 12a. It can be seen that many small particle-like phases appear at the edge of the river pattern, which is identified as the TiAl₃ phase by EDS analysis results, as shown in Table 3. Wei et al^[35] reported that the particle-like TiAl₃ phase has weak bonding effect with the Al6061 substrate, resulting in the lower joint

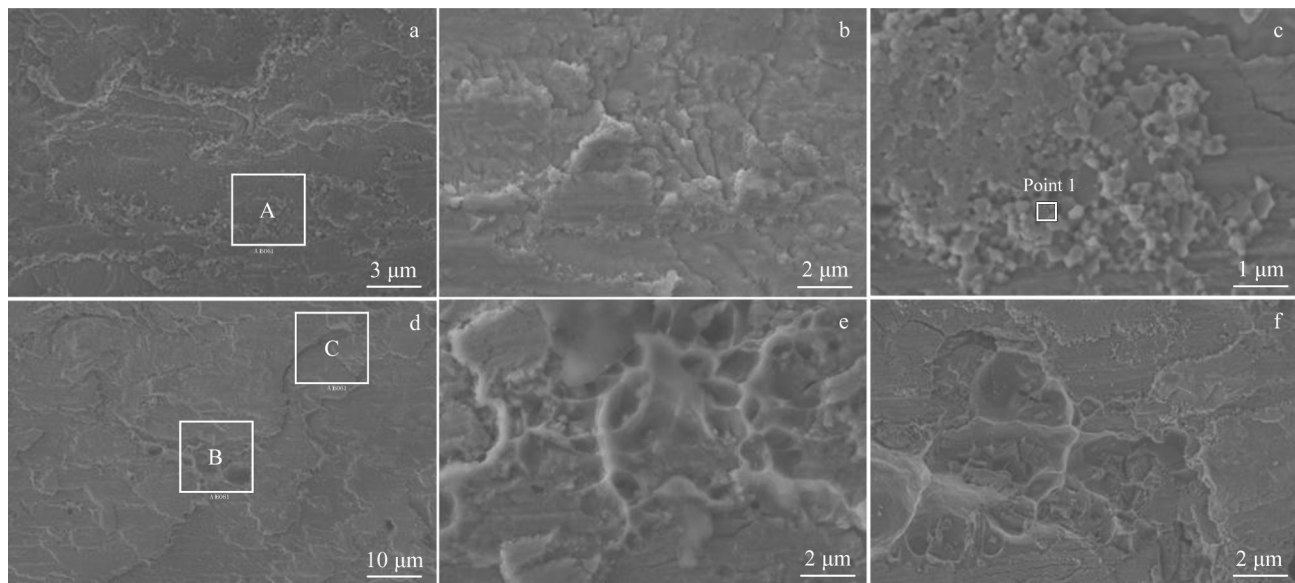


Fig. 12 Tensile fracture morphologies of TC4/Al6061 joint prepared by HIP diffusion bonding at Al6061 substrate side (a–b) and at TC4 substrate side (d); magnified images of area A in Fig.12a (c), area B (e), and area C (f) in Fig.12d

Table 3 EDS analysis results of point 1 in Fig.12c

Element	wt%
Al	66.45
Ti	23.57
Si	7.49
Mg	2.49

strength. A lot of cleavage steps (Fig. 12d) appear in the fracture surface of Al6061 substrate side. Fig. 12e–12f show the magnified images of the rectangular areas in Fig. 12d. Both ductile and brittle fracture characteristics can be observed, such as dimples and tearing edges in Fig. 12e and 12f, respectively. According to XRD analysis of the fracture surface on the Al6061 substrate side, the fracture surface is primarily composed of Al phase, which possesses excellent plasticity and exhibits tough fracture characteristics. The existence of Ti-Al intermetallic compounds leads to the overall brittle fracture of the tensile fracture surface.

3 Conclusions

1) The TC4/Al6061 joint with no obvious macroscopic defects can be prepared by HIP diffusion bonding. The elements of the two substrates undergo mutual diffusion and metallurgical reactions, generating Ti-Al intermetallic compounds with different thicknesses. The interface consists of $TiAl_3$ phase ($0.2 \mu m$), $TiAl$ phase ($2 \mu m$), and Ti_3Al phase ($0.5 \mu m$). Under the driving force of chemical potential, Si atoms are segregated in the diffusion transition zone of the interface. Mg atoms are segregated in the interface zone near Al6061 substrate side.

2) $TiAl_3$ phase has the lowest effective heat of formation energy through EHF model, which is formed firstly during the metallurgical reaction. With increasing the Ti content in the

diffusion transition zone, the chemical potential of Si atoms is decreased, leading to the Si segregation in the diffusion transition zone.

3) The Ti-Al intermetallic compounds with higher hardness are formed at the TC4/Al6061 joint interface. The TC4/Al6061 joint has the maximum tensile strength of 144 MPa, and the brittle fracture is the dominant fracture mode. The TC4/Al6061 joint fractures at the diffusion layer on the Al6061 substrate side or at the interior of Al6061 substrate side.

References

- Chen Y H, Liu D Y, Cao W M et al. *Rare Metal Materials and Engineering*[J], 2017, 46(S1): 36
- Hourmand M, Sarhan A A D, Sayuti M et al. *Arabian Journal for Science and Engineering*[J], 2021, 46: 7087
- Li Qian, Wen Lingyou, Tan Yaning et al. *Rare Metal Materials and Engineering*[J], 2022, 51(11): 4093 (in Chinese)
- Santos M C, Machado A R, Sales W F et al. *The International Journal of Advanced Manufacturing Technology*[J], 2016, 86: 3067
- Chen Shuhai, Li Liqun, Chen Yanbin. *Rare Metal Materials and Engineering*[J], 2010, 39(1): 32 (in Chinese)
- Zhang Z J, Huang J, Fu J P et al. *Journal of Materials Processing Technology*[J], 2022, 302: 117502
- Gu X, Cui M, Chen J et al. *Journal of Materials Research and Technology*[J], 2021, 13: 2202
- Song Linling. *Optimization of Welding Parameters During Ti-TA2/5A06Al Dissimilar Double-Sided Cold Arc MIG Welding*[D]. Taiyuan: North University of China, 2022 (in Chinese)
- Gadakh V S, Badheka V J, Mulay A S. *Proceedings of the*

- Institution of Mechanical Engineers, Part L*[J], 2021, 235(8): 1757
- 10 Zhang Zhongke, Wu Jingwei, Zhao Huaxia. *The Chinese Journal of Nonferrous Metals*[J], 2020, 30(4): 739 (in Chinese)
- 11 Zhang L C, Chen L Y, Wang L. *Advanced Engineering Materials*[J], 2020, 22(5): 1901258
- 12 Liu M F, Zhang C S, Meng Z J et al. *Composites Part B: Engineering*[J], 2022, 230: 109507
- 13 Kar A, Suwas S, Kailas S V. *Materials Science and Engineering A*[J], 2018, 733: 199
- 14 Guo Xunzhong, Fan Minyu, Liu Zhongli et al. *Rare Metal Materials and Engineering*[J], 2017, 46(5): 1192 (in Chinese)
- 15 Atkinson H V, Davies S. *Metallurgical and Materials Transactions A*[J], 2000, 31(12): 2981
- 16 Xiao Y, Lang L, Xu W et al. *Journal of Materials Research and Technology*[J], 2022, 19: 1789
- 17 Yu H, Lu C, Tieu A K et al. *Materials Science and Engineering A*[J], 2016, 660: 195
- 18 Li B, Shen Y F, Luo L et al. *Journal of Alloys and Compounds*[J], 2016, 658: 904
- 19 Miedema A R, De Chatel P F, De Boer F R. *Physica B+C*[J], 1980, 100(1): 1
- 20 Pretorius R, Reus R, Vredenberg A M et al. *Materials Letters*[J], 1990, 9(12): 494
- 21 Hao Xiaohu. *Microstructure and Mechanical Properties of TC4 Titanium Alloy/304 Stainless Steel Sheets Gas Tungsten Arc Welded Joint*[D]. Dalian: Dalian University of Technology, 2020 (in Chinese)
- 22 Xu L, Cui Y Y, Hao Y L et al. *Materials Science and Engineering A*[J], 2006, 435: 638
- 23 Assari A H, Eghbali B. *Journal of Alloys and Compound*[J], 2019, 733: 50
- 24 Wang Z W, Shen J Q, Hu S S et al. *Optics & Laser Technology*[J], 2022, 149: 107867
- 25 Chen Shuhai. *Research on Technology and Mechanism of Laser Welding-Brazing for Ti/Al Dissimilar Alloys*[D]. Harbin: Harbin Institute of Technology, 2009 (in Chinese)
- 26 Perk J H H, Capel H W. *Physica A: Statistical Mechanics & Its Applications*[J], 1980, 100(1): 1
- 27 Yeheskel B. *Handbook of Pure Substances Thermodynamic and Physical Properties*[M]. Beijing: Science Press, 2003 (in Chinese)
- 28 Tanaka T, Gokcen N A, Morita Z. *Zeitschrift Fur Metallkunde*[J], 1990, 81(1): 49
- 29 Pretorius R, Vredenberg A M, Saris F W et al. *Journal Applied Physics*[J], 1991, 70(7): 3636
- 30 Laik A, Bhanumurthy K, Kale G B. *Intermetallics*[J], 2004, 12: 69
- 31 Luo J G, Acoff V L. *Materials Science and Engineering A*[J], 2004, 379(1-2): 164
- 32 Kattner U R, Lin J C, Chang Y A. *Metallurgical Transactions A*[J], 1992, 23: 2081
- 33 Luo G Q, He J Y, Song Z F et al. *Journal of Materials Engineering and Performance*[J], 2019, 28: 1226
- 34 Alhazaa A, Albrithen H, Hezam M et al. *Crystals*[J], 2022, 12(9): 1293
- 35 Wei Y, Wu A P, Zou G S et al. *Materials Science and Engineering A*[J], 2008, 480(1-2): 456

TC4钛合金与Al6061铝合金热等静压扩散连接接头的界面特征及力学性能

麻相龙¹, 曹睿¹, 董浩², 王铁军², 闫英杰¹

(1. 兰州理工大学 省部共建有色金属先进加工与再利用国家重点实验室, 甘肃 兰州 730050)

(2. 安泰科技股份有限公司, 北京 100081)

摘要: 对TC4钛合金和Al6061铝合金的异种金属进行了热等静压扩散连接实验, 研究了TC4/Al6061连接接头的界面特征、形成机制和力学性能, 并通过热力学分析解释相关实验现象。结果表明, 热等静压扩散连接及后续退火处理后, 两侧母材元素发生了明显的互扩散, 其中Si、Mg元素在化学势驱动力作用下分别富集于扩散过渡区和Al侧界面。接头界面发生冶金反应生成TiAl₃、TiAl、Ti₃Al等金属间化合物, 通过有效生成热模型计算表明TiAl₃相优先生成。硬度实验表明界面生成的Ti-Al金属间化合物具有较高的硬度。拉伸实验显示接头最大抗拉伸强度达到了144 MPa。

关键词: TC4钛合金; Al6061铝合金; 热等静压扩散连接; 界面特征; 力学性能

作者简介: 麻相龙, 男, 1998年生, 博士生, 兰州理工大学省部共建有色金属先进加工与再利用国家重点实验室, 甘肃 兰州 730050, E-mail: maxianglong0706@163.com