



# Microstructures and mechanical properties of TiAl/Ni-based superalloy joints brazed with Fe-based filler metal

H. S. Ren<sup>1</sup> · H. P. Xiong<sup>1</sup> · L. Ye<sup>1</sup> · X. Y. Ren<sup>1</sup> · W. W. Li<sup>1</sup> · R. Y. Qin<sup>1</sup>

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## Abstract

For the purpose of high-temperature service potential and the weight reduction expectation in aviation engineering applications, dissimilar joining of TiAl alloy to Ni-based superalloy has been conducted with a newly designed Fe-based filler metal. The microstructure and chemical composition at the interfaces were investigated by SEM, EPMA, and XRD. The filler metal consisted of Fe-based solid solution and a small amount of precipitated (Fe, Cr)<sub>ss</sub>. The wettability experiment results showed that the filler metal presented a stronger reaction tendency and more sufficient spreading behavior on Ni-based superalloy than on TiAl alloy. The brazed joint was composed of TiAl diffusion affected zone, Ni<sub>3</sub>Al, TiCo, borides, (Ni, Fe, Co, Cr)<sub>ss</sub>, and  $\gamma$ -TiAl dissolved with Ni. A stronger reaction tendency occurred between Ni and TiAl substrate due to the lower dissolution enthalpies of element Ni in melts of Ti and Al. The joints brazed at 1180 °C/5 min presented a shear strength of 267 MPa at room temperature.

**Keywords** TiAl alloy · Ni-based superalloy · Brazing · Microstructure · Mechanical properties

## 1 Introduction

TiAl alloy is a potential structural material for aerospace applications due to its relatively low density, high specific strength, excellent creep behavior, and good oxidation resistance at elevated temperature [1, 2]. Its long-term service temperature can be up to 760~850 °C. Because of its high-temperature service potential as well as the weight reduction effect, TiAl alloy is inclined to be applied as the candidate material for heat-resistance components in advanced aero-engines [3]. At present, Ni-based superalloys are extensively used in aero-engine hot-section components. Hence, the joining between TiAl alloy and Ni-based superalloy to produce dissimilar joints is of great interest to achieve the optimal material combination design.

For the joining of TiAl alloy to themselves, methods of fusion welding [4, 5], brazing [6, 7], and diffusion bonding [8, 9] were used. However, the weldability was limited by its poor ductility and damage tolerance at room temperature. It was reported that only small pieces were available for butt joints. This was related not only with its intrinsic brittleness but also with the high residual stress generated by welding thermal cycle [10]. Hence, cracking issue was always encountered when TIG welding, laser welding, and electron beam welding methods were applied. For these welding methods, preheat treatment at the temperature of high up to 800 °C is usually needed for the cracking prevention [11]. In general, it is believed that furnace vacuum brazing and diffusion bonding are the suitable joining techniques without the cracking problem.

With regard to dissimilar joining, some efforts were focused on the joining of TiAl alloys to Ti-based alloys or steels. For instance, dissimilar diffusion bonding TiAl to Ti6Al4V was carried out using Ni/Al nanolayers at 700~800 °C [12]. A thin bond interface (less than 10  $\mu$ m) was obtained and was mainly composed of NiAl grains. Shiue et al. investigated the brazing of Ti<sub>50</sub>Al<sub>50</sub> to Ti-6Al-4 V (wt%) alloy with Ti-Cu-Ni system filler metals [13]. The dissimilar joint mainly consisted of Ti-rich phase and Ti<sub>2</sub>Ni and interfacial Ti<sub>3</sub>Al phases. The joint shear

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✉ H. S. Ren  
seawater2011@163.com

<sup>1</sup> Welding and Plastic Forming Division, Beijing Institute of Aeronautical Materials, Beijing 100095, China

**Table 1** Chemical composition of K24 superalloy (wt%)

Co	Cr	Al	V	Mo	W	Ti	Nb	Ni
12.0~15.0	8.5~10.5	5.0~5.7	4.2~4.7	2.7~3.4	1.0~1.8	0.5~1.0	0.5~1.0	Balance

strength was deteriorated by the formation of  $Ti_2Ni$  and  $Ti_3Al$  phases. Dong et al. studied the dissimilar metal vacuum brazing between TiAl alloy and 40Cr steel with  $Ti_{60}Ni_{22}Cu_{10}Zr_8$  (at.%) alloy foil as filler [14]. TiAl and TiNi compounds within the TiAl/40Cr joint limited the joint strength, and the maximum shear strength was only 32 MPa.

Actually, the dissimilar joining of TiAl alloy to Ni-based superalloy is more attractive for engineering applications because of its high-temperature service potential as well as the weight reduction effects [15]. Nevertheless, the dissimilar joining is extremely difficult due to the following reasons: the thermal expansion coefficient of Ni-based superalloy ( $\sim 13.0 \times 10^{-6} K^{-1}$ ) is substantially higher than that of the TiAl alloy ( $\sim 8.7 \times 10^{-6} K^{-1}$ ). Chemical composition is a parameter that varies over a wide range across the TiAl/Ni-based superalloy joint. It is difficult to obtain a joint which has good compatibility with the two materials simultaneously. The dissolution enthalpy of Ti in liquid Ni solvent is up to  $-170$  kJ/mol [16], meaning a strong reactivity between Ti and Ni. TiNi binary and Al-Ti-Ni ternary intermetallic compounds could be formed in the joint.

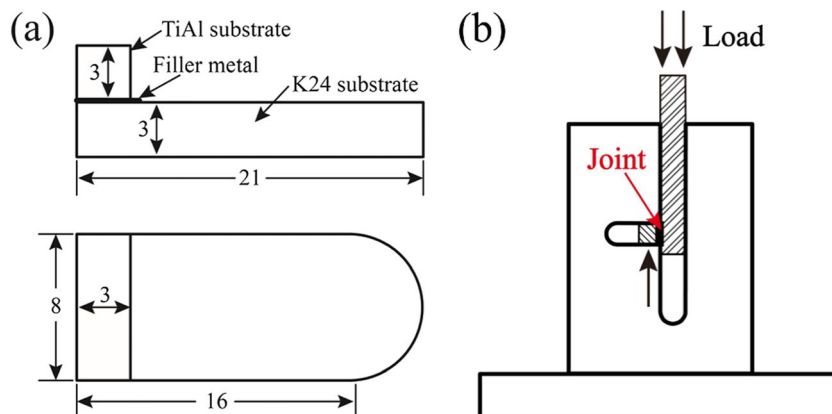
As reported in inference [17], Ag-27.5Cu-12.5In-1.25Ti (wt%) filler metal was used to join  $\gamma$ -TiAl and In718 superalloy. In the  $\gamma$ -TiAl/In718 joint,  $AlNi_2Ti$  and  $AlCu_2Ti$  reaction layers were visible adjacent to  $\gamma$ -TiAl and In718 base metals. The joint brazed at  $730^\circ C/10$  min presented a shear strength of 228 MPa at room temperature. Besides, the dissimilar joining of a  $Ti_3Al$ -based alloy to a Ni-based superalloy was stud-

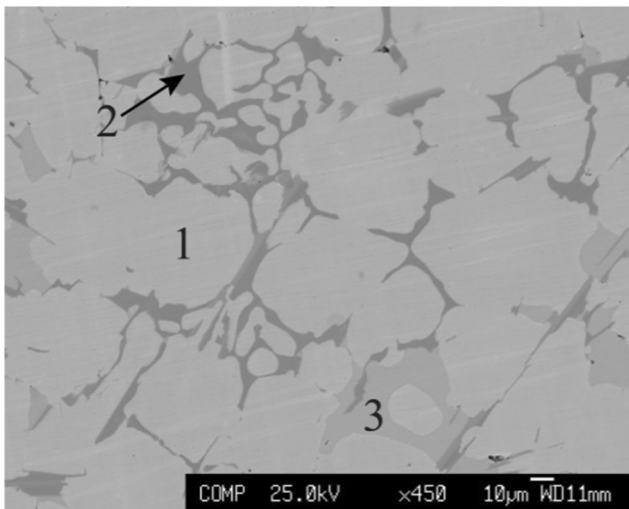
ied using Ag-21Cu-25Pd (wt%) filler metal [18]. Due to the strong affinity, element Pd mainly reacted with the  $Ti_3Al$  substrate and formed intermetallic compounds of TiPd,  $Ti_3Pd_5$ , and AlPd. And element Ag was enriched in the joint central area as (Ag, Cu)<sub>ss</sub>. Even the joint tensile strength reached 404 MPa at room temperature, and the strength of 158 MPa at  $600^\circ C$  was obtained. Generally speaking, Ag-based filler metals are often used for operation temperatures under  $400^\circ C$ . These TiAl/Ni or  $Ti_3Al$ /Ni joints obtained through Ag-based filler metals cannot serve at the temperatures above  $700^\circ C$ .

In addition, an amorphous  $Zr_{58.6}Al_{15.4}Ni_{20}Co_6$  foil was fabricated and applied as the filler metal to join TiAl and a Ni-based alloy [19]. The maximum shear strength of the braze joint at room temperature and  $600^\circ C$  were 353 MPa and 214 MPa, respectively.

In the present study, a FeNiCoCrSiB system filler metal was designed and used for brazing of TiAl alloy to Ni-based superalloy. Continuous solid solution can be formed between element Fe and Co with Ni. Si and B are added as melting-point depressant. More importantly, the dissolution enthalpies of Ti and Al in liquid Fe solvent is  $-82$  kJ/mol and  $-47$  kJ/mol, obviously lower than Ti and Al in liquid Ni solvent ( $-170$  kJ/mol and  $-96$  kJ/mol) [16]. It is believed that this system filler metal could control the reactivity tendency between the two base metals. Thus, the Fe-based filler metal was designed and adopted. The interfacial microstructure and mechanical properties of the joints were investigated.

**Fig. 1** Illustration of shear test for bonded joints: **a** geometry of shear test sample in mm and **b** shear test setup





**Fig. 2** Backscattered electron image of FeNiCoCrSiB filler metal

## 2 Experimental procedures

The TiAl alloy used was Ti–48Al–2Cr–2Nb (at.%) composed of  $\alpha_2$ -Ti<sub>3</sub>Al and  $\gamma$ -TiAl phases. The other base material to be joined in this experiment was K24 superalloy with long-term service temperature of 900 °C. The chemical composition of K24 superalloy is given in Table 1. The liquidus temperature of Fe-(10~15)Ni-(9~13)Co-(9~13)Cr-(3~6)Si-(1~4)B filler alloy was measured by differential thermal analysis (DTA). The filler alloy was fabricated into foils with a thickness of about 60  $\mu\text{m}$  by a rapid solidification technique, and double foils were laminated in one joint specimen.

Wettability experiment of this filler metal on base metals was carried out at 1180 °C for 10 min. Prior to brazing experiment, the joined samples and filler foils were ultrasonically cleaned in acetone. During the joining experiment, the vacuum was kept between  $7 \times 10^{-3}$  Pa and  $8 \times 10^{-4}$  Pa and the heating rate was 10 °C/min. Two brazing temperatures of 1140 °C and 1180 °C were chosen with brazing times of 5 min and 10 min. After the brazing experiment, the joint was cooled down to 500 °C with a rate of 5 °C/min and then followed by furnace cooling.

The mechanical characterization was performed by shear test. The shear strength was measured at room temperature and 750 °C, respectively. Details of the joint specimen and the illustration of the shear test are shown in Fig. 1. The re-

ported average strength was obtained from at least three joints. The joint microstructures and the cross-sections of the joints subjected to the shear test were examined using a scanning electron microscope (SEM) equipped with an electron probe micro-analyzer (EPMA). Furthermore, the fractured surface of the joints was also analyzed using an X-ray diffraction (XRD) spectrometer.

## 3 Results and discussion

### 3.1 Microstructure of TiAl/K24 joints

According to DTA analysis results, the melting range of the Fe-Ni-Co-Cr-Si-B filler alloy was 1085~1120 °C. Figure 2 shows the backscattered electron image of this filler metal, and three phases are visible. Based on the EPMA analysis results (Table 2), the filler metal mainly consists of Fe-based solid solution in which Ni, Co, Cr, and Si were dissolved (“1,” “3”). A small amount of (Fe, Cr)ss precipitates in microzone “2.”

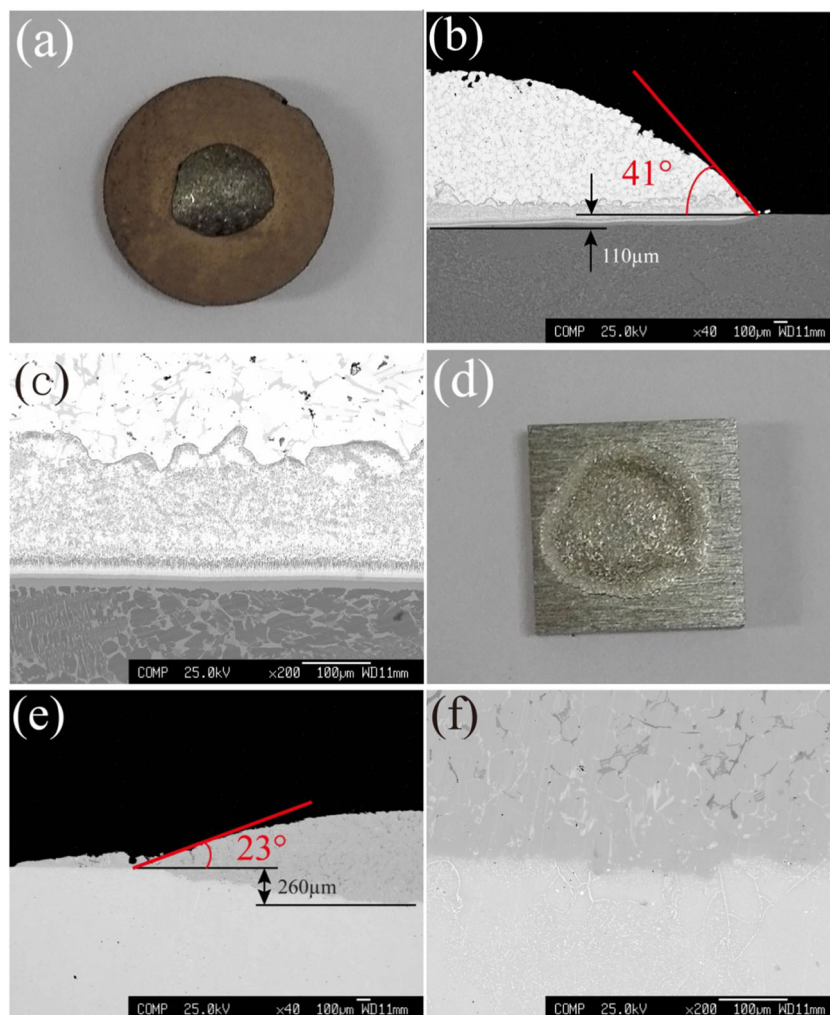
Figure 3 presents the wettability experiment results of FeNiCoCrSiB filler metal on TiAl and Ni-based superalloy (K24). As can be seen in Fig. 3a and d, the filler metal melted and reacted with both base metals. On the one hand, the maximum penetration in the TiAl alloy is about 110  $\mu\text{m}$ . Several reaction layers could be observed at the interface (Fig. 3c). On the other hand, it can be seen in Fig. 3e that the maximum penetration of the filler metal into Ni-based superalloy is about 260  $\mu\text{m}$ , much deeper than for the TiAl alloy. Moreover, compared with the TiAl sample in Fig. 3c, there are no reaction layers in the Ni-based sample in Fig. 3f. This illustrates that a stronger reaction and sufficient spreading behavior of filler metal occurred on the Ni-based superalloy. Hence, the contact angle on the Ni-based superalloy (23°) is much smaller than that on TiAl alloy (41°).

Table 3 displays the dissolution enthalpies of the elements Fe, Ni, Co, and Cr in melts of Ti and Ni. The reaction between element Cr and Ti is weak. However, the element Ni could react with Ti strongly [16]. Thus, several reactive layers are visible in Fig. 3c. Moreover, sound compatibility can be obtained between the filler metal and Ni-based superalloy since Ni, Co, and Cr are the common alloying elements in the two

**Table 2** EPMA analysis results for the microzones in Fig. 2 (at.%)

Microzones	Fe	Ni	Co	Cr	Si	Deduced phases
1	59.70	13.12	8.92	8.02	10.25	Fe-based solid solution
2	51.15	0.89	3.41	44.50	0.05	(Fe, Cr)ss
3	53.92	17.83	11.44	3.95	12.87	Fe-based solid solution

**Fig. 3** Wettability of FeNiCoCrSiB filler metal on TiAl and K24 at 1180 °C/10 min: **a, b, c** TiAl alloy; **d, e, f** K24 Ni-based superalloy



alloys. Based on these reasons, the filler metal displayed a lower contact angle and better spreading behavior on the Ni-based superalloy.

Figure 4 shows the microstructures of the brazed TiAl/K24 joints. For the joint brazed at the condition of 1140 °C/5 min (Fig. 4a), the filler metal reacted with the TiAl substrate. However, cracks formed adjacent to TiAl interface. Besides, voids were visible at the interface between filler metal and

K24 superalloy. It is indicated that the reactions between the filler metal than parent materials were insufficient. When the brazing temperature was raised to 1180 °C, defects such as cracks and voids were absent. The joint thickness increased from 110 μm (Fig. 4a) to 170 μm (Fig. 4b). With the prolongation of the dwell time at the brazing temperature, the joint thickness was increased further. The joint thickness in Fig. 4c was about 200 μm. Besides, few micro-cracks can be observed at the interface between the filler metal and the TiAl base metal.

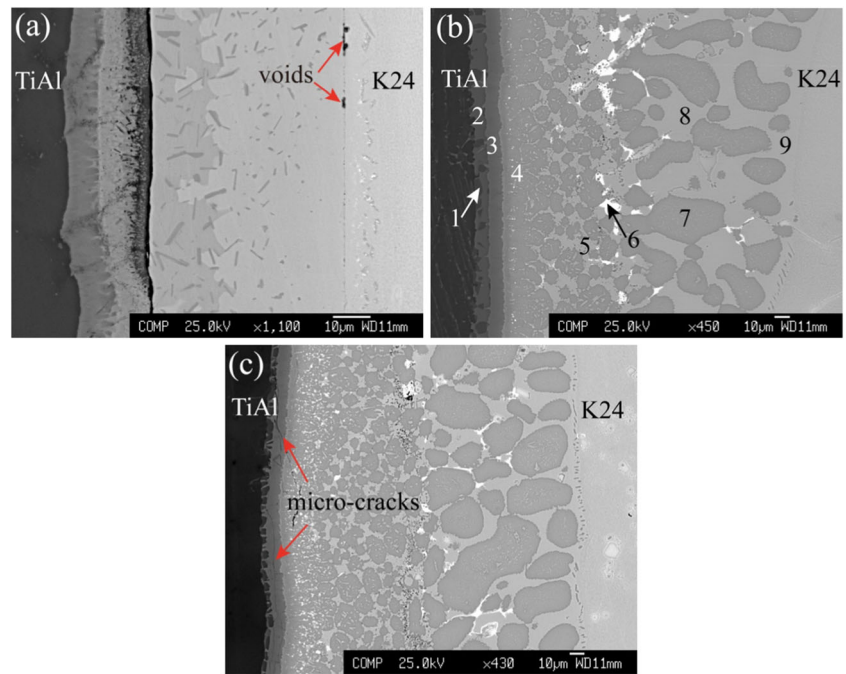
EPMA analysis results for the typical microzones in Fig. 4b are listed in Table 4. Ti and Al are the main elements in microzone “1” and a little amount of Nb and Cr is visible. Thus, these zones should be the TiAl diffusion affected zone. Besides Ti and Al, 15.57 at.% Ni was detected in microzone “3.” This is caused by the diffusion of Ni from the filler metal into the TiAl substrate. This phase is identified as  $\gamma$ -TiAl in which Ni is dissolved. Moreover, it should be pointed out that

**Table 3** Dissolution enthalpies of elements Fe, Ni, Co, and Cr in melts of Ti, Al, and Ni (kJ/mol) [16]

Elements	Fe	Ni	Cr	Co
Ti	-70	-140	-32	-115
Ni	-6	0	-27	-1
Al	-48	-81	-36	-68



**Fig. 4** Backscattered electron images of TiAl/K24 joints brazed at **a** 1140 °C/5 min, **b** 1180 °C/5 min, and **c** 1180 °C/10 min



the concentrations of Fe, Co, and Cr in microzone “3” are obviously lower than that of Ni (Table 4). As shown in Table 3, the dissolution enthalpies of element Ni in melts of Ti and Al are much lower than that of Fe, Co, and Cr, indicating a larger diffusion force for Ni towards TiAl base metal and a stronger reaction tendency between Ni and TiAl substrate. As a result, more Ni was detected in microzone “3.”

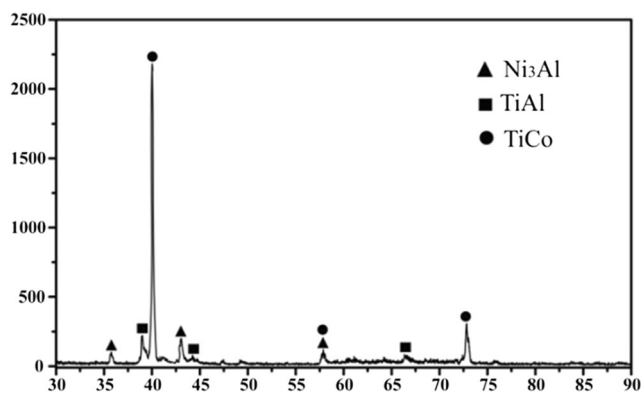
The main element in microzones “4” and “5” is Ni. Al, Ti, and Co are also the major alloying elements in microzone “4.” Hence, it is deduced that NiAl and TiCo phases might be formed in this zone. Ni<sub>3</sub>Al and TiCo phases were confirmed on the XRD spectrum as illustrated in Fig. 5. The phase in microzone “5” is defined as (Ni, Fe, Co, Cr) solid solution. Fe is the main component in the present filler metal. However, a

much higher concentration of Ni than Fe was detected in microzones “3,” “4,” and “5,” indicating that these Ni atoms came from the Ni-based superalloy and part of the superalloy adjacent to the joining interface has been substantially dissolved into the brazed seam.

In the center of the joint, some white phases were visible. EPMA analysis results indicated that element B was enriched in the area. Both Cr and Mo are boride forming elements [20]. According to Table 4, these phases were deduced to be Cr-B and Mo-B compounds. During the transient liquid phase (TLP) bonding of cast IN718 nickel-based superalloy using Ni-7Cr-4.5Si-3Fe-3.2B amorphous interlayer, Cr-Mo-rich boride was also formed [21]. Similar to microzone “4,” phases in microzone “7” were Ni<sub>3</sub>Al and TiCo. Moreover, (Ni, Fe, Co,

**Table 4** EPMA analysis results for the microzones in Fig. 4b (at.%)

Microzones	Ti	Al	Nb	Ni	Fe	Cr	Co	Si	B	Mo	W	V	Deduced phases
1	60.12	34.64	1.73	0.44	0.24	1.95	0.14	/	0.45	0.01	/	0.28	TiAl diffusion affected zone
2	58.40	32.96	2.08	1.23	0.66	3.97	0.39	/	/	0.03	/	0.28	
3	35.58	37.93	1.60	15.57	3.52	3.31	2.25	0.05	/	/	/	0.18	γ-TiAl(Ni)
4	12.14	21.15	0.52	40.24	7.37	7.40	9.57	0.40	/	0.64	0.13	0.45	NiAl, TiCo
5	6.10	6.45	0.29	42.17	14.65	14.85	12.74	0.49	/	1.30	0.23	0.74	(Ni, Fe, Co, Cr)ss
6	6.10	0.08	1.39	4.71	14.65	19.75	2.44	/	40.37	14.42	4.10	2.27	Cr-B, Mo-B
7	9.64	19.81	0.21	45.25	7.61	5.87	12.66	0.48	/	0.52	0.09	0.46	NiAl, TiCo
8	6.30	7.03	0.23	42.15	14.35	14.34	12.66	0.52	/	1.30	0.32	0.79	(Ni, Fe, Co, Cr)ss
9	4.98	3.60	0.45	46.22	18.80	13.77	13.93	0.21	/	2.42	1.08	0.79	



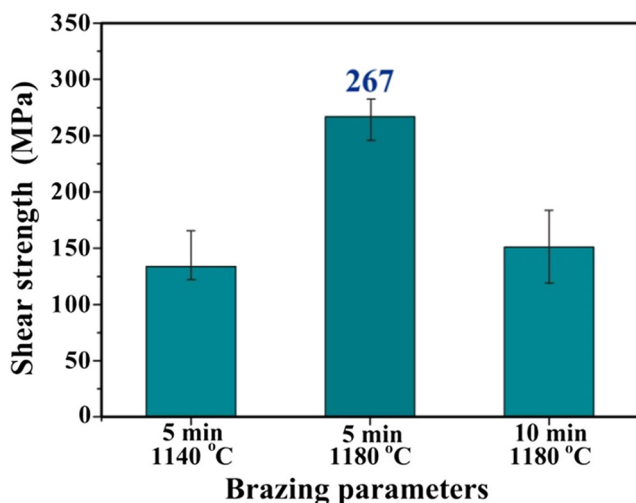
**Fig. 5** XRD pattern of the fractured surface for specimen brazed at 1180 °C/5 min

Cr)ss was formed in microzones “8” and “9.” Hence, the joint was mainly composed of TiAl diffusion effected zone,  $\gamma$ -TiAl in which Ni is dissolved, Ni<sub>3</sub>Al, TiCo, borides, and (Ni, Fe, Co, Cr)ss.

As mentioned above, the reactivity tendencies Ti and Al with Fe are lower than Ti and Al with Ni. In the joint, TiNi binary and Al-Ti-Ni ternary intermetallic compounds were not detected. Multi-component solid solutions were formed. In the joined area, which is a relatively wide zone, adjacent to K24 superalloy, the joint composition and microstructure are close to the K24 superalloy. However, the abrupt change in composition and microstructure between TiAl alloy and brazed seam is visible. It is detrimental to the joint strength.

### 3.2 Shear strength of the TiAl/K24 joints

Figure 6 displays the effect of brazing parameters on shear strength of TiAl/K24 joints. The joints brazed at 1140 °C/



**Fig. 6** Shear strengths of the TiAl/K24 joints brazed under different brazing conditions

5 min showed a low shear strength of 134 MPa. As can be seen in Fig. 4a, cracks occurred adjacent to the TiAl interface and voids were visible at the K24 superalloy interface. The reactions between the filler metal and two base metals were not sufficient. This kind of microstructure deteriorated the joint strength. As the brazing parameter of 1180 °C/5 min was applied, the joint strength increased to 267 MPa. However, when the dwell time was prolonged to 10 min at 1180 °C, the joint strength decreased to 151 MPa. It might be related to the micro-cracks formed adjacent to the TiAl substrate. For the joint brazed at 1180 °C/5 min, the shear test was conducted at 750 °C. The result indicated that the joint average strengths reached 219 MPa, about 82% of the strength at room temperature.

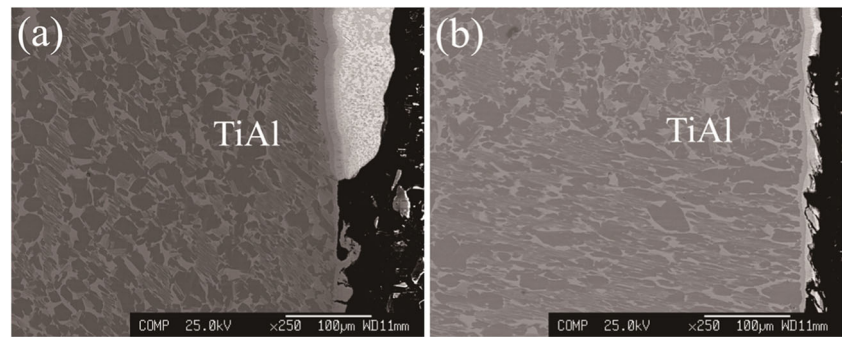
In a previous study, titanium foil with a thickness of 80  $\mu$ m was used for reactive brazing between TiAl and Ni-based superalloy [22]. A joint shear strength of 258 MPa was obtained, equivalent to the present study. Titanium foil reacted with both base metals, and the phases TiNi, AlNi<sub>2</sub>Ti, Ti<sub>2</sub>Ni, and Al<sub>3</sub>NiTi<sub>2</sub> were formed. Increasing the brazing temperature or prolonging the dwell time further lead to the formation of these brittle intermetallic layers. In another study, a V/Cu composite interlayer was applied in the laser welding of TiAl alloy and Ni-based superalloy [23]. This interlayer decreased the formation of brittle phases. And the joint tensile strength at room temperature and 600 °C were 230 MPa and 145 MPa, respectively. In general, the TiAl/Ni joints strength should be improved further and more research work is supposed to be carried out.

In order to identify the fracture location of the TiAl/K24 joints, the specimens were inspected after shear testing. For the joint brazed at 1180 °C/5 min, it mainly fractured at the TiAl diffusion affected zone and central area as shown in Fig. 7a. Concerning the joint brazed at 1180 °C/10 min, it mainly fractured in the  $\gamma$ -TiAl phase in which Ni was dissolved (Fig. 7b). This is consistent with the microstructure in Fig. 4c where a few micro-cracks are visible within the formed  $\gamma$ -TiAl phase. In general, due to the abrupt change in composition and microstructure between TiAl alloy and brazed seam, the interface adjacent to TiAl alloy is the weak link of the joint.

## 4 Conclusions

Dissimilar joining of TiAl alloy to cast Ni-based superalloy was conducted with a newly designed Fe-based filler metal. Microstructures and mechanical properties of the joints have been investigated. Primary conclusions are summarized as follows:

**Fig. 7** Fracture surface (TiAl side) of the TiAl/K24 joints brazed at **a** 1180 °C/5 min and **b** 1180 °C/10 min



- (1) The melting range of Fe-Ni-Co-Cr-Si-B filler alloys was 1085–1120 °C. It consisted mainly of Fe-based solid solution in which Ni, Co, Cr, and Si are dissolved, and a small amount of precipitated (Fe, Cr)ss was visible.
- (2) The filler metal presented a stronger reaction and more sufficient spreading behavior on the Ni-based superalloy than on the TiAl alloy. Its contact angle on Ni-based superalloy under the heating condition of 1180 °C/10 min was 23° and that on TiAl alloy was 41°.
- (3) The brazed TiAl/Ni joint was composed of TiAl diffusion affected zone, Ni<sub>3</sub>Al, TiCo, borides, (Ni, Fe, Co, Cr)ss, and  $\gamma$ -TiAl in which Ni is dissolved. The joints brazed at 1180 °C/5 min presented a shear strength of 267 MPa at room temperature.

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