Infrared Brazing Ti₅₀Ni₅₀ and Ti-6Al-4V Using the BAg-8 Braze Alloy

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Microstructure evolution, reaction path and shear strength of infrared brazed Ti₅₀Ni₅₀ shape memory alloy and Ti-6Al-4V joints using BAg-8 braze alloy have been investigated. The braze alloy can readily wet on Ti-6Al-4V, but not on Ti₅₀Ni₅₀. Titanium dissolves from Ti-6Al-4V to enhance the wettability of braze alloy on Ti₅₀Ni₅₀ during brazing. The joint is mainly comprised of hypoeutectic silver and copper for specimens infrared brazed below 850°C. Silver does not react with both substrates, but copper is readily alloyed with titanium and reacts vigorously to form TiCu₄, Ti₃Cu₄, TiCu and Ti₂Cu phases in Ti-6Al-4V side and form CuNiTi phase in Ti₅₀Ni₅₀ side. The dramatic microstructure change of joint is observed for specimens infrared brazed at 900°C above 60 s due to the extensive Ti₂Ni presence. The average shear strength of the specimens infrared brazed below 850°C is about 200 MPa. Although the presence of interfacial CuNiTi phase is beneficial to the wettability of molten braze alloy on Ti₅₀Ni₅₀ substrate, it is detrimental to the bonding strength of the infrared brazed Ti₅₀Ni₅₀/BAg-8/Ti-6Al-4V joint.

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1. Introduction

Ti-6Al-4V, which uses aluminum and vanadium as stabilizers, can be strengthened by solution and aging heat treatments to achieve higher specific strength and fracture toughness than steels and other titanium alloys. In addition to its superior mechanical properties and biocompatibility, Ti-6Al-4V can be easily welded, machined and forged, so it is widely applied in aerospace, the defense industry and medical fields.¹⁻⁴⁾

As a functional material, Ti₅₀Ni₅₀ shape memory alloy (SMA) with equiatomic composition is well known for its excellent shape memory and superelasticity.⁵⁻⁷⁾ In addition to these unique behaviors, its high corrosion resistance and biocompatibility have led to the wide use of Ti₅₀Ni₅₀ SMA in medical, safety and robotics applications.^{8,9)} Numerous reports have intensively studied the martensitic transformation and mechanical properties of Ti₅₀Ni₅₀ SMA as affected by the addition of a ternary element or the various thermomechanical treatments such as cold working and thermal cycling.¹⁰⁻¹²⁾

The joining of Ti₅₀Ni₅₀ and Ti-6Al-4V alloys can be potentially applied in the manufacture of golf club head. A conventional golf club head consists of a main body and a striking plate. The golf club head is usually made by the titanium alloy due to its high specific strength. In contrast, Ti₅₀Ni₅₀ alloy is one of shape memory alloys, and it features with its superelasticity as well as high damping capacity. Accordingly, it is a potential alloy applied in the striking plate of a golf club head.

Brazing¹³⁻¹⁵⁾ and welding¹⁶⁾ are two methods used to join Ti₅₀Ni₅₀ alloy with other alloys, mainly depending upon the application temperature range. Most SMAs are used below 100°C because the starting temperature of martensitic transformation, Ms, of Ti₅₀Ni₅₀ SMAs is less than about 60°C.¹⁰⁾ Therefore, instead of welding, it is quite suitable for Ti₅₀Ni₅₀ SMAs to be joined by brazing through the formation

of a multilayer phase to eliminate a fusion zone in the joint. Compared with the traditional furnace brazing, infrared brazing can precisely study the mechanism and microstructural evolution of the brazed joint due to its very rapid heating rate, as high as 3000°C per minute, and its low total heat input. Thus, in recent years, infrared brazing has been widely applied in studying the kinetics of brazing process.¹⁷⁻²³⁾

The selection of filler material plays an important role in brazing Ti₅₀Ni₅₀ and titanium alloy due to the high reactivity of the titanium with many other elements. The wettability of the braze alloy, the formation of intermetallic phases in the joint and the mechanical properties of these intermetallics must all be considered in the selection of the filler metal used in brazing. The commercial silver-copper eutectic braze alloy (BAg-8) is well known for its use in joining stainless steels, titanium alloys and nickel-based alloys.²¹⁻²⁴⁾ Chan *et al.*¹⁹⁾ suggested that the BAg-8 alloy can effectively wet the Ti-6Al-4V substrate at 850°C in the dynamic sessile drop test. However, Wu and Wayman²⁵⁾ indicated that there is no solubility of silver in the Ti₅₀Ni₅₀ alloy. It is reported that the wettability of silver-copper eutectic braze can be significantly improved with minor titanium additions of 1–5 mass%.^{26,27)} Accordingly, the joining of Ti₅₀Ni₅₀ and Ti-6Al-4V using the silver-based braze alloy is possible because the titanium can be transported from the Ti-6Al-4V into the molten braze during the infrared brazing.

This study concentrates on an innovative approach of joining Ti₅₀Ni₅₀ and Ti-6Al-4V by infrared brazing using the BAg-8 braze alloy. The microstructure evolution, phase reaction and shear strength of the infrared brazed joints are comprehensively studied to access the relation between the microstructure and joint performance.

2. Experiment Procedures

Equiatomic Ti₅₀Ni₅₀ SMA was prepared by vacuum arc remelting (VAR) of high purity (>99.9 mass%) titanium rods and nickel pellets. Prior to VAR, titanium rods and nickel pellets were cleaned by 1HF–15HNO₃–64H₂O (in mL) and

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saturated NaOH solution, respectively. Vacuum arc remelting of the master alloy was performed at least six times, and the final mass loss of the ingot was less than 0.1 mass%. The $\text{Ti}_{50}\text{Ni}_{50}$ ingot was subsequently homogenized at 850°C for 100 h in order to reduce the segregation of the alloy. The chemical composition of Ti-6Al-4V in mass percentage was 5.76% aluminum, 4.03% vanadium, 0.28% iron, 0.06% carbon and titanium balance. BAg-8 foil purchased from Lucas-Milhaupt Inc. was used as the brazing filler metal. According to the specifications of American Welding Society, the composition of BAg-8 braze alloy in mass percent is (71–73) silver and copper balance with 780°C eutectic temperature.²⁶⁾ The thickness of braze alloy was $50\mu\text{m}$ throughout the experiment.

The infrared brazing equipment used in this study was ULVAC SINKO-RIKO RHL-P610C which provides much faster thermal cycles and less damage to the base metal than conventional furnace brazing. Infrared brazing was performed in high vacuum of 5×10^{-3} Pa, and the heating rate was set at $900^\circ\text{C}/\text{min}$ throughout the experiment. All specimens were preheated at 600°C for 60 s to equilibrate actual temperature and set temperature.

The size of brazed specimens was cut to be $10.0 \times 10.0 \times 2.5\text{ mm}$ by low speed diamond saw. All joined surfaces were polished by SiC papers up to grit 600 and ultrasonically cleaned with acetone before infrared brazing. The area of filler metal foil was approximately the same as that of base metals. A graphite fixture was used in this study to enhance the absorption of infrared rays during infrared brazing. Specimens were sandwiched between two graphite plates, and an R-type thermal couple in the upper graphite plate was used to contact with brazed specimen.

A schematic diagram of graphite fixture used for the shear test is shown in Fig. 1 which shows that the middle piece of shaded area is $\text{Ti}_{50}\text{Ni}_{50}$, and the other two pieces next to the middle piece are Ti-6Al-4V substrate. Two black bold lines between $\text{Ti}_{50}\text{Ni}_{50}$ and Ti-6Al-4V are the braze alloy with the width of 1.5 mm. Shear tests of infrared brazed joints were performed using a Shimadzu AG-10 universal testing machine. The infrared brazed specimen was compressed at a constant speed of 1 mm/min. The cross section of the brazed specimens was examined by either LEO 1530 field emission scanning electron microscope (FESEM) or Philips XL-30 scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). Quantitative chemical analyses were performed using a JEOL JXA 8600SX electron probe microanalyzer (EPMA) equipped

with a wavelength dispersive spectrometer (WDS) with spot size of 1 micron and operational voltage of 20 kV.

3. Results and Discussion

3.1 Microstructure evolution of infrared brazed $\text{Ti}_{50}\text{Ni}_{50}/\text{BAg-8}/\text{Ti-6Al-4V}$ joint

Figure 2 shows the SEM backscattered electron images (BEIs) of $\text{Ti}_{50}\text{Ni}_{50}/\text{BAg-8}/\text{Ti-6Al-4V}$ specimen infrared brazed at 800°C for 40, 60, 90, 120 and 180 s. These results are consistent with previous research that showed most of the brazed region is silver–copper hypoeutectic, primary silver and silver–copper eutectic.¹⁷⁾ According to the SEM BEIs, the silver does not react with both substrates during infrared brazing because the white silver-rich matrix is not in contact with both substrates. Additionally, there are interfacial reaction layers on both sides of substrates, and the reaction layers on the side of Ti-6Al-4V substrate are thicker than on the $\text{Ti}_{50}\text{Ni}_{50}$ side, indicating that vigorous metallurgical reactions occurred on the Ti-6Al-4V side. In Fig. 2, the thickness of some brazed specimens is less than the original thickness of BAg-8 foil ($50\mu\text{m}$) due to overflow of the molten braze out of joint during the infrared brazing.

Figure 3 shows SEM BEIs and EPMA chemical analysis results of the specimen infrared braze at 800°C for 40 s. There is one continuous reaction layer formed close to $\text{Ti}_{50}\text{Ni}_{50}$ substrate, as marked by A in Fig. 3(a). The chemical composition of point A consists of copper, titanium and nickel in the phase. According to the isothermal section of Cu–Ni–Ti ternary phase diagram in Fig. 4, the stoichiometry of phase A is close to the CuNiTi phase.²⁸⁾ The CuNiTi phase can also be expressed as $(\text{Cu}_x\text{Ni}_{1-x})_2\text{Ti}$ where x is between 0.23 and 0.75 in atomic percent.²⁹⁾ The phase marked by B in Fig. 3(a) is the copper-rich phase next to the interfacial CuNiTi phase, and it is widely observed in the hypoeutectic silver–copper matrix. According to the binary phase diagrams of Ag–Cu and Cu–Ti, the highest solubility of silver and titanium in the copper matrix is 8 at% and 5 at% at 800°C , respectively.³⁰⁾ This is consistent with the current EPMA analysis of the copper-rich phase, in which the copper-rich phase is alloyed with minor silver and titanium.

The silver–copper hypoeutectic microstructure shown in Fig. 2(a) is caused by the depletion of the copper content from the silver–copper eutectic braze due to the reaction between copper and titanium during the infrared brazing.¹⁷⁾ Three consecutive interfacial reaction layers close to the Ti-6Al-4V substrate were observed, as marked by D, E and F in Fig. 3(b), and they were identified as TiCu_4 , Ti_3Cu_4 and TiCu phases in the EPMA chemical analysis. Based on the isothermal section of Ag–Cu–Ti ternary phase diagram at 700°C ,²⁸⁾ the silver has minor solubility in TiCu_4 , Ti_3Cu_4 and TiCu phases, which is consistent with the experimental observations shown in Fig. 3.

Figure 5 shows SEM BEIs and EPMA chemical analysis results of multi-reaction layers of the infrared brazed specimen at 850°C for 15, 90 and 180 s. Both Ti_3Cu_4 and TiCu phases, as marked by A and B in Fig. 5(a), respectively, are observed at the interface for the 15 s brazed specimen. For the specimen infrared brazed at 90 s, as shown in Fig. 5(b), Ti_3Cu_4 , TiCu and Ti_2Cu can be found, as marked by D, E and

Fig. 1 The schematic diagram of shear test specimen.

Fig. 2 SEM BEIs of Ti₅₀Ni₅₀/BAg-8/Ti-6Al-4V specimens infrared brazed at 800°C for (a) 40, (b) 60, (c) 90, (d) 120 and (e) 180 s.

F, respectively. The interfacial Ti₂Cu phase is formed between TiCu and the Ti-6Al-4V substrate. The Ti₃Cu₄ phase shown in Figs. 5(a) and (b) is replaced by the TiCu phase when the brazing time is increased to 180 s, as marked H in Fig. 5(c). In summary, the evolution of interfacial reaction layers on the Ti-6Al-4V side at 850°C is changed from Ti₃Cu₄ and TiCu phases into TiCu and Ti₂Cu phases with increasing the brazing time up to 180 s.

Figure 6 shows SEM BEIs and EPMA chemical analysis results for the interface between the Ti₅₀Ni₅₀ and BAg-8 brazo alloy at 850°C for different brazing time. The existence of a continuous CuNiTi reaction layer close to the Ti₅₀Ni₅₀ substrate is independent of the brazing time. In contrast, the copper-rich phase (marked by B) next to the interfacial CuNiTi (marked by A) for the specimen brazed at 15 s is changed into Ti₃Cu₄ (marked by D) at 90 s and AlCu₂Ti (marked by F) at 180 s, respectively.

The increase of brazing temperature accelerates micro-

structure evolution of brazed joints, so higher infrared brazing temperature was also performed in the test. Figure 7 shows SEM BEIs of Ti₅₀Ni₅₀/BAg-8/Ti-6Al-4V specimen infrared brazed at 900°C for 15, 30, 60, 90, 120 and 180 s, respectively. The joint thickness varies from less than 50 μm at the early stage of infrared brazing to nearly 100 μm at 180 s. This can be explained by overflowing from the low melting point silver-copper eutectic of the joint at 900°C, so the thickness of joint is decreased at the early stage brazing. By increasing the brazing time at 900°C, a large amount of titanium is transported from substrates into the molten braze, where it reacts with the remaining braze alloy, to increase the thickness of brazed joint.

Compared to the initial brazing period at 800 and 850°C, the silver-copper eutectic changed to hypoeutectic in the joint was not observed at 900°C, indicating more vigorous microstructure evolution than at lower temperature. According to the EPMA chemical analysis results shown in Fig. 7,

Fig. 3 SEM BEIs and EPMA chemical analysis results of $\text{Ti}_{50}\text{Ni}_{50}/\text{BAg-8}/\text{Ti-6Al-4V}$ specimen in atomic percent infrared brazed at 800°C for 40 s: (a) the $\text{Ti}_{50}\text{Ni}_{50}/\text{BAg-8}$ side and (b) $\text{BAg-8}/\text{Ti-6Al-4V}$ side.

Fig. 4 The isothermal sections of Cu–Ni–Ti at 800°C in atomic percent.²⁸⁾ (The Δ is CuNiTi intermetallic phase)

the molten braze reacted with both substrates to form continuous reaction layers. Ti_2Cu , TiCu , Ti_3Cu_4 and TiCu_4 are formed sequentially from the Ti–6Al–4V side into the braze alloy, in the order from the highest titanium concentration into the lowest titanium concentration. On the other hand, Ti_3Cu_4 and CuNiTi are observed at the interface close to the $\text{Ti}_{50}\text{Ni}_{50}$ substrate. After increasing the brazing time above 60 s, the BEIs show dramatic change in microstructure, as illustrated in Figs. 7(c)–(f). It is noticeable that there are large numbers of lamellar-like structures in the interface between Ti–6Al–4V and BAg–8 braze alloy for the specimen infrared brazed at 900°C for 60 s. Figure 8 shows the SEM BEIs and EPMA chemical analysis results for lamellar-like structures under high magnification. Referring to Fig. 4, the

chemical composition of points A and B in Fig. 8 is Ti_2Ni phase alloyed with minor aluminum and copper contents. After 60 s, the extensive presence of Ti_2Ni phase and Ti rich phase was observed in the braze up to 180 s. Based on the experimental observation, vigorous metallurgical reactions exist among the braze alloy and two substrates at 900°C . Table 1 summarizes the phase evolution of infrared brazed $\text{Ti}_{50}\text{Ni}_{50}/\text{BAg-8}/\text{Ti-6Al-4V}$ joints for various brazing conditions.

3.2 Reaction path of infrared brazed $\text{Ti}_{50}\text{Ni}_{50}/\text{BAg-8}/\text{Ti-6Al-4V}$ joint

The sessile drop test was employed in Fig. 9 using an approximately 0.12 g BAg–8 ball with near spherical shape on the $\text{Ti}_{50}\text{Ni}_{50}$ substrate heated to 1000°C and held for 270 s. Moreover, the sandwich infrared brazing of $\text{Ti}_{50}\text{Ni}_{50}/\text{BAg-8}/\text{Ti}_{50}\text{Ni}_{50}$ specimen has been performed at 900°C for 180 s. The joint was debonded after infrared brazing. The poor wettability of the molten BAg–8 braze alloy is clearly observed in the test. In contrast, the Ti–6Al–4V substrate can easily be wetted by the molten BAg–8 braze alloy.¹⁹⁾ The Ti–6Al–4V substrate can be readily dissolved into the molten braze during infrared brazing. Accordingly, the dissolution of titanium from substrates into the molten braze can become an active element to enhance the wettability of the braze alloy on the $\text{Ti}_{50}\text{Ni}_{50}$ substrate.

The amount of titanium dissolved into the molten braze is strongly dependent upon the time and temperature of brazing. Based on the experimental results, the reaction layers mainly consist of titanium and copper. The silver in the braze has little effect on the interfacial reaction. For the assumption of equilibrium state in cooling cycle of the experiment, the liquidus projection of Ag–Cu–Ti ternary phase diagram illustrated in Fig. 10 can offer the first approach of the reaction path in the joint. According to Fig. 10, there is a large miscibility gap in the Ag–Cu–Ti ternary liquidus

Element (at%)	A	B	C	D	E	F	G	H	I
Cu	55.8	46.6	10.1	56.3	47.8	30.7	11.7	48.1	30.0
Ag	1.7	1.0	89.9	2.6	3.4	2.0	---	3.2	1.8
Al	5.0	1.9	---	---	1.8	7.5	13.8	---	6.2
Ti	37.5	50.5	---	41.1	47.0	59.8	66.3	48.7	62.0
V	---	---	---	---	---	---	8.2	---	---
Possible phase	Ti ₃ Cu ₄	TiCu	Ag-rich	Ti ₃ Cu ₄	TiCu	Ti ₂ Cu	Ti-rich	TiCu	Ti ₂ Cu

Fig. 5 SEM BEIs and EPMA chemical analysis results of the interface between the BAg-8 and Ti-6Al-4V substrate in atomic percent after infrared brazing at 850°C for (a) 15, (b) 90 and (c) 180 s.

projection, and it plays a crucial role on studying mechanism of active brazing.²⁷⁾ The solidification of molten braze at approximately 850°C is shown below:²⁸⁾

It is important to note that the chemical composition of the liquid (*l*) in (1) contains 30 at% silver, 61 at% copper and 9 at% titanium. According to our experimental results, the

Element (at%)	A	B	C	D	E	F
Cu	53.3	85.6	54.7	54.70	53.7	52.5
Ag	2.1	5.8	1.6	1.9	1.2	2.0
Al	---	2.8	---	4.2	---	16.4
Ti	32.2	5.8	31.5	34.8	31.1	24.0
Ni	12.4	---	12.2	4.4	14.0	5.1
Possible phase	CuNiTi	Cu-rich	CuNiTi	Ti ₃ Cu ₄	CuNiTi	AlCu ₂ Ti

Fig. 6 SEM BEIs and EPMA chemical analysis results of the interface between the Ti₅₀Ni₅₀ and BAg-8 braze alloy in atomic percent after infrared brazing at 850°C for (a) 15, (b) 90 and (c) 180 s.

silver-copper eutectic braze is easily alloyed with the titanium. For the specimen infrared brazed at 800°C, the dissolution of titanium from Ti-6Al-4V substrate in the braze alloy is not obvious at 40 s, as shown in Fig. 3(b). Therefore, in Fig. 3, the braze is alloyed with little titanium content, and the interfacial Ti₃Cu₄ phase should be solidified from the molten braze. This is consistent with (1).

Based on Fig. 10, the reaction schemes followed by the eq. (1) are shown below:²⁸⁾

Fig. 7 SEM BEIs and EPMA chemical analysis results of Ti₅₀Ni₅₀/BAg-8/Ti-6Al-4V specimen infrared brazed at 900°C for (a) 15, (b) 30, (c) 60, (d) 90, (e) 120 and (f) 180 s.

The molten braze further reacts with the Ti₃Cu₄, and finally forms silver-rich, copper-rich and TiCu₄ phases, as shown in Fig. 3(b). It is also important to note that the

peritectic reaction may cause remaining silver-rich phase to be trapped inside the TiCu₄ and Ti₃Cu₄ phases, as marked by arrows in Fig. 3(b). Additionally, the irregular shape of TiCu₄ and Ti₃Cu₄ phases indicates the solidification of TiCu₄ and Ti₃Cu₄ is from liquid phase.

Mercier and Melton³¹⁾ suggested a high copper solubility is up to 25 at% in Ti₅₀Ni₅₀ at 155°C. According to our

Element (at%)	Cu	Ag	Al	Ti	Ni	Possible phase
A	3.5	---	3.7	66.0	26.8	Ti ₂ Ni
B	2.2	---	6.0	64.0	27.8	Ti ₂ Ni
C	13.8	2.5	6.6	57.8	19.3	Ti ₂ Ni
D	16.3	0.8	4.1	51.0	27.8	---
E	4.7	1.4	11.2	76.4	6.3	Ti-rich

Fig. 8 SEM BEI and EPMA chemical analysis results of the interface between Ti-6Al-4V and BAg-8 braze alloy in atomic percent at 900°C for 60 s.

Table 1 Summary of phase evolution in the infrared brazed joint.

Brazing temperature (°C)	Brazing time (s)	Phase formation from Ti ₅₀ Ni ₅₀ into Ti-6Al-4V substrate
800	30–180	CuNiTi–Cu–(Ag,Cu) hypoeutectic–TiCu ₄ –Ti ₃ Cu ₄ –TiCu
850	15, 30, 60	CuNiTi–Cu–(Ag,Cu) hypoeutectic–Ti ₃ Cu ₄ –TiCu–Ti ₂ Cu
850	90	CuNiTi–Ti ₃ Cu ₄ –(Ag,Cu) hypoeutectic–Ti ₃ Cu ₄ –TiCu–Ti ₂ Cu
850	120, 180	CuNiTi–AlCu ₂ Ti–(Ag,Cu) hypoeutectic–TiCu–Ti ₂ Cu
900	15	CuNiTi–(Ag,Cu) hypoeutectic–TiCu ₄ –Ti ₃ Cu ₄ –TiCu–Ti ₂ Cu
900	30	CuNiTi–Ti ₃ Cu ₄ –(Ag,Cu) hypoeutectic–TiCu ₄ –Ti ₃ Cu ₄ –TiCu–Ti ₂ Cu
900	60	Ti ₂ Ni + Ti ₂ Cu
900	90, 120, 180	Ti ₂ Ni + Ti

experimental observations, the copper phase in molten braze reacts with the Ti₅₀Ni₅₀ substrate and forms the CuNiTi intermetallic phase next to the Ti₅₀Ni₅₀ substrate, as illustrated in Fig. 3(a). The formation of CuNiTi phase is consistent with the isothermal section of Cu–Ni–Ti ternary phase diagram because both Ti₅₀Ni₅₀ and CuNiTi phases are in contact, as illustrated in Fig. 4.

For the specimen infrared brazed at 850°C, both Ti₃Cu₄ and TiCu phases were solidified from liquid with irregular shape, as shown in Fig. 5. Based on the experimental results, the growth rate of TiCu is much higher than that of Ti₃Cu₄, and the Ti₃Cu₄ phase was gradually replaced by TiCu phase after increasing the brazing time to 180 s, as illustrated in Fig. 5(c). The interdiffusion between TiCu and Ti-6Al-4V substrate results in the formation of Ti₂Cu phase. However, the Ti₂Cu cannot be accurately analyzed due to the limited lateral resolution in the EPMA analysis. Based on Fig. 4,

Fig. 9 The dynamic sessile drop test of BAg-8 ball on the Ti₅₀Ni₅₀ substrate at 1000°C for 270 s.

Fig. 10 The liquids projection and its reaction scheme of Ag–Cu–Ti.²⁸⁾

there is no boundary curve between titanium and Ti₃Cu₄ phase, and both TiCu and Ti₂Cu phases are located between Ti₃Cu₄ and titanium.²⁸⁾ Accordingly, the experimental observation is consistent with the phase diagram.

Similar to the specimen infrared brazed at 800°C, the Ti₅₀Ni₅₀ substrate reacts with copper in the molten braze to form interfacial CuNiTi stable phase at the 850°C (Fig. 6). According to the experimental observation, the copper-rich phase next to CuNiTi phase is replaced by the continuous Ti₃Cu₄ phase at 90 s, and AlCu₂Ti phase at 180 s, as shown in Figs. 6(a)–(c). Based on the Cu–Ni–Ti isothermal section, as

Al-Cu-Ti

- 1 AlCuTi
- 2 AlCu₂Ti
- 3 AlCu₃Ti
- 4 Al₂CuTi₂
- 5 Al₁₁CuTi₄
- ?Al₃CuTi

Fig. 11 The isothermal section of Al-Cu-Ti at 500°C.²⁸⁾

displayed in Fig. 4, the CuNiTi phase is in contact with both copper and Ti₃Cu₄ phases, and there is a high solubility of aluminum in copper up to 20 at%, as illustrated in Al-Cu-Ti isothermal section of Fig. 11.²⁸⁾ Similar to the transport of titanium from the Ti-6Al-4V substrate into the molten braze, the aluminum is also dissolved from Ti-6Al-4V substrate during the brazing. Consequently, the existence of Ti₃Cu₄ phase at 120 s is replaced by AlCu₂Ti phase at 180 s, as shown in Fig. 6(c).

The microstructure of a joint infrared brazed at 900°C for 15 and 30 s is similar to that infrared brazed at 850°C. However, the microstructure of a joint brazed at 900°C for 60 s has changed into Ti₂Ni and titanium-rich phases, as shown in Fig. 8. Figure 7(c) shows there are no clear interfacial layers in the joint representing the decomposition of substrates above 60 s, resulting in large amounts of titanium and nickel dissolved into the braze. According to Fig. 4, there is not the same boundary curve between titanium and TiNi phase, and the TiNi phase shares the boundary curve with CuNiTi and Ti₂Ni phases. This is consistent with the phases that existed in the joint. According to the Ti-Ni binary phase diagram,³⁰⁾ there is a reaction at 942°C shown in (5):

It is important to note that the chemical composition of the liquid in (5) is 90 at% titanium and 10 at% nickel. This is consistent with our experimental observation. The huge amount of titanium and nickel dissolved from both substrates results in the formation of Ti₂Ni phase for the specimen infrared brazed at 900°C after 60 s, as illustrated and marked by H in Fig. 7(f).

3.3 Mechanical evaluation of infrared brazed Ti₅₀Ni₅₀/BAg-8/Ti-6Al-4V joint

Table 2 shows the shear strength of Ti₅₀Ni₅₀/BAg-8/Ti-6Al-4V joints infrared brazed at 800, 850 and 900°C for 180 s. The shear test of the specimen infrared brazed at 900°C could not be performed accurately due to the significantly

Table 2 Shear strengths of joints infrared brazed at various temperatures for 180 s.

Brazing Temperature (°C)	800	850	900*
Shear strength (MPa) – specimen 1	193	182	—
Shear strength (MPa) – specimen 2	219	202	—
Average shear strength (MPa)	206	192	—

* significantly eroded Ti-6Al-4V substrate

Fig. 12 Cross section of the shear test specimen infrared brazed 800°C for 180 s: (a) BEI and (b) SE image.

eroded Ti-6Al-4V substrate after infrared brazing, and this was also observed in a previous study.¹⁸⁾ The average shear strength of the specimen infrared brazed at 800°C is 206 MPa, and that infrared brazed at 850°C is 192 MPa. The difference of average shear strength is not obvious, because there is no significant difference between the microstructures of infrared brazed joints.

The cross section of the fractured specimen was mounted in an epoxy and examined using an SEM. Figure 12 shows both the BEI and the secondary electron (SE) image of the fractured specimen infrared brazed at 800°C after the shear test. The crack can be observed clearly within the interfacial CuNiTi phase between the braze alloy and Ti₅₀Ni₅₀ substrate. For the specimen infrared brazed at 850°C, the crack also initiated at the same phase. Accordingly, it can be seen that the presence of CuNiTi phase is detrimental to the infrared brazed joint.

Figure 13 shows SEM fractographs and EPMA chemical

At%	Cu	Ag	Al	Ti	Ni	Possible phase
A	12.1	87.9	---	---	---	Ag-rich
B	45.1	1.0	1.7	37.0	15.2	CuNiTi
C	11.8	88.2	---	---	---	Ag-rich
D	37.9	3.3	2.4	35.0	21.4	CuNiTi

Fig. 13 SEM fractographs and EPMA chemical analysis results for specimens infrared brazed at (a) 800 and (b) 850°C.

analysis results for specimens infrared brazed at 800 and 850°C, respectively. There are sliding marks on the ductile silver-rich matrix, as marked by A and C in Fig. 13. In contrast, many transverse cracks are observed at the CuNiTi phase, as marked by B and D in the figure. Although the presence of interfacial CuNiTi phase is beneficial to the wettability of the molten braze alloy on the Ti₅₀Ni₅₀ substrate, it deteriorates the bonding strength of the infrared brazed Ti₅₀Ni₅₀/BAg-8/Ti-6Al-4V joint.

4. Conclusions

The microstructural evolution, reaction phase and shear strength of the joints are thoroughly studied on the infrared brazed Ti₅₀Ni₅₀ and Ti-6Al-4V alloy using the BAg-8 braze alloy. The important conclusions are summarized below.

- (1) The braze alloy can readily wet the Ti-6Al-4V substrate, but poor wetting on the Ti₅₀Ni₅₀ substrate was observed during the sessile drop test. However, the titanium that dissolved from Ti-6Al-4V into the molten braze early in the brazing time can become an active element to enhance the wettability of the braze alloy on the Ti₅₀Ni₅₀ substrate.
- (2) The infrared brazed joint is mainly comprised of hypoeutectic silver and copper for specimens infrared

brazed below 850°C. The silver is reacted with neither substrates. In contrast, the copper is readily alloyed with the titanium and reacts vigorously with both substrates to form interfacial reaction layers. Interfacial TiCu₄, Ti₃Cu₄, TiCu and Ti₂Cu phases are observed at the interface between BAg-8 and Ti-6Al-4V substrate. The Ti₅₀Ni₅₀ substrate also reacts with copper in the braze to form CuNiTi phase and its thickness is independent of brazing time.

- (3) The dramatic microstructure change of the brazed joint is observed for the specimen infrared brazed at 900°C above 60 s. The extensive presence of Ti₂Ni phase in the joint is caused by the huge amount of titanium and nickel dissolved from both substrates. Serious overflow of the molten braze and the erosion of both substrates make it unsuitable for infrared brazing Ti₅₀Ni₅₀ and Ti-6Al-4V at 900°C.
- (4) The average shear strength of the specimen infrared brazed at 800°C is 206 MPa, and that infrared brazed at 850°C is 192 MPa. The variation of the average shear strength is not obvious because there is no significant difference between the microstructures of infrared brazed joints. The presence of CuNiTi phase is detrimental to the bonding strength of infrared brazed joint.

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