Note

Infrared Brazing Titanium Alloys Using Clad Ti–15Cu–15Ni Fillers with Different Clad Layers

Chuen-Yi CHIOU,¹⁾ Ren-Kae SHIUE¹⁾ and C. Steve CHANG²⁾

1) Department of Materials Science and Engineering, National Taiwan University, Taipei 106, Taiwan. E-mail: rkshiue@ntu.edu.tw
2) Engineered Materials Solutions, 39 Perry Avenue, MS 4-1, Attleboro, MA 02703-2410, USA.

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1. Introduction

The brazing of Ti alloys using Ti-based filler metals has been extensively studied in the last 15 years.^{1–4)} Based on the previous studies, the use of Ti-based braze alloys is considered as one of the best technique in brazing Ti alloys due to their high bonding strength,^{3,5–8)} in which Ti–15Cu–15Ni is frequently used as a Ti-based braze alloy. Infrared vacuum brazing has been proven to be a useful method to investigate the microstructural evolution of the brazed joint due to its high heating rate up to 50°C/s.^{3,4)} It has been reported that the microstructural evolution of infrared vacuum brazed Ti alloy using Ti–15Cu–15Ni primarily depends on the redistribution of both Cu and Ni in the joint.^{3,4)}

Commercial Ti-based braze alloys are available mostly in the powder form, even though foils have many obvious advantages, as it is difficult to obtain foils by the conventional metal working process.^{8–10)} Amorphous ribbons are seldom used in industry because of its high production cost. Alternatively, a cold roll-bonding process was applied to combine Ti, Cu and Ni strips into a layered composite that allows conventional cold rolling process to produce the Ti–15Cu–15Ni brazing foil.⁹⁾ The melting behavior of clad Ti–15Cu–15Ni braze foil is affected by chemical composition, stacking sequence and total number of clad layers, and it still needs further study.

Ti–15V–3Cr–3Al–3Sn (Ti–15-3) is a β -Ti alloy developed to reduce processing cost by substituting strip for sheet due to its excellent formability at room temperature, and Ti–4.5Al–3V–2Mo–2Fe (SP-700) is a β -rich α – β titanium alloy developed to yield a superplastic formability at 700°C.¹⁰⁾ Both are important engineering Ti alloys.

The purpose of this investigation is focused on the microstructural evolution of infrared vacuum brazing Ti–15-3 and SP-700, respectively. Three types of clad Ti–15Cu–15Ni filler foils with different clad layers in composition, thickness and sequence are tested under various brazing conditions and compared.

2. Experimental Procedures

The base metals used in the experiment were Ti–15-3 and SP-700 plates with the dimension of 10×10×1 mm and 15×15×3 mm, respectively. Three types of clad Ti–15Cu–15Ni foil in wt% with 100 mm wide and 50 μ m thick were used as the brazing filler metals. **Table 1** gives the sequential layers of these filler foils. Type I foil comprised 7 clad layers with the sequence of C713/N440/C713/Ti/C713/N440/C713. Both C713 and N440 were commercially available Cu–Ni alloys, and their chemical compositions were shown in **Table 2**. Type II foil comprised 3 clad layers with the sequence of Ti/50Cu–50Ni/Ti. Type III foil consists of 7

Table 1. Clad Ti–15Cu–15Ni brazing foils with different clad layers.

Filler Metal Type	Sequence of Clad Layers
I	C713/N440/C713/Ti/C713/N440/C713
II	Ti/50Cu–50Ni/Ti
III	Ni/Cu/Ni/Ti/Ni/Cu/Ni

Table 2. Chemical composition of C713 and N440 alloys used in the clad layers.

wt%	Cu	Ni	Al	C	Fe	Mn	Pb	Si	Zn
C713	71.25–76.5	23.5–26.5	0	0	≤0.2	≤1	≤0.05	0	≤1
N440	32	66	0.02	0.1	1	0.5	0	0.25	0

Fig. 1. EPMA BEIs of type I clad brazing foil: (a) overview of the cross section, (b) high magnification of selected area near the surface in (a).

clad layers of pure Cu, Ni and Ti with the sequence of Ni/Cu/Ni/Ti/Ni/Cu/Ni.

Infrared brazing Ti–15-3 and SP-700 substrates were performed in the experiment, respectively. The heating rate used in infrared brazing was kept at 10°C/s throughout the experiment, and all samples were preheated at 900°C for 600 s before heating up to the brazing temperature. Specimens were brazed at 949, 970 and 1 000°C for 300 s, 600 s and 1 200 s under a vacuum of 5×10^{-3} Pa. The cross section of the brazed samples were cut by a low-speed diamond saw and prepared by a standard procedure for metallographic observations. The microstructure of the brazed joints was examined using a JEOL JXA 8600SX electron probe microanalyzer (EPMA) equipped with wavelength dispersive spectroscopy (WDS). The acceleration voltage was 15 kV, and its minimum spot size was 1 μ m.

3. Results and Discussion

Figure 1 displays EPMA backscattered electron images (BEIs) of type I clad brazing foil. Because the difference of atomic weight between Cu and Ni is as low as one, C713 and N440 layer cannot be distinguished in the BEIs. As shown in **Fig. 1(b)**, however, the presence of these layers was checked by the EPMA chemical analysis. The clad sequence of seven layers in type I brazing foil was confirmed as C713/N440/C713/Ti/C713/N440/C713.

Figure 2 shows EPMA BEIs of type II clad brazing foil. Based on the line scan results of Ti, Ni and Cu, there are three layers in the clad foil. The clad sequence of type II brazing foil is Ti/50Cu–50Ni/Ti. **Figure 3** shows EPMA BEIs of type III clad brazing foil. The brazing foil consists of 7 layers of pure metals, and the clad sequence of type III brazing foil is Ni/Cu/Ni/Ti/Ni/Cu/Ni. Because the Ni has better oxidation resistance than Cu, the Ni clad layer was chosen as the outer surface of the Ti–15Cu–15Ni braze alloy.

Figure 4 shows EPMA BEIs and chemical analysis results of Ti–15-3 joint using three types of clad filler metals under various infrared brazing conditions. The spot size used in the EPMA chemical analysis was 1 μ m, and it was much smaller than the phases identified. It is expected that EPMA analysis results provide acceptable accuracy in

Fig. 2. EPMA BEIs of type II clad brazing foil: (a) overview of the cross section, (b) high magnification of selected area in (a), (c) Ti, Ni, Cu line scans in (b).

Fig. 3. EPMA BEIs of type III clad brazing foil: (a) overview of the cross section, (b) high magnification of selected area near the surface in (a), (c) Ti, Ni, Cu line scans in (b).

phase identification. Although higher magnification of micrographs can specify the location examined by electron beam more accurately, photographs with lower magnification were selected for the purpose of comparing microstructural evolution of brazed joints. Microstructures of brazed joints are strongly related to the infrared brazing conditions. The brazed joint consists of at least two readily distinguished phases, white intermetallic phase and Ti-rich matrix. Based on the Cu–Ni–Ti ternary phase diagram, the Ti-rich molten braze solidified and underwent a eutectic reaction at 900°C upon cooling cycle of brazing¹¹:

Accordingly, eutectic Ti_2Cu and Ti_2Ni are formed in the

Location / (at%)	Al	Cr	Cu	Ni	Sn	Ti	V	Primary Phase(s)
A	0.4	0.5	5.0	21.8	0.0	70.9	1.1	Ti_2Ni
B	1.9	1.0	7.6	6.5	0.3	78.8	4.0	Ti-rich
C	3.3	1.8	4.3	4.0	0.6	78.4	7.6	Ti-rich
D	0.5	0.5	4.8	23.1	0.0	69.9	1.1	Ti_2Ni
E	1.8	1.0	6.6	6.4	0.3	79.5	4.4	Ti-rich
F	3.6	2.0	3.9	3.8	0.6	78.6	7.7	Ti-rich
G	1.5	0.6	2.9	27.0	0.0	66.6	1.4	Ti_2Ni
H	1.2	0.2	15.6	15.1	0.0	65.8	2.0	$\text{Ti}_2\text{Cu} + \text{Ti}_2\text{Ni}$
I	3.9	1.9	2.6	5.1	0.3	77.3	8.9	Ti-rich
J	3.8	2.0	3.3	4.5	0.7	77.1	8.8	Ti-rich

Fig. 4. EPMA BEIs and chemical analysis results of Ti-15-3 joint using type I filler infrared brazed at (a) 949°C for 300 s, (b) 970°C for 600 s, (c) 1000°C for 1200 s; type II filler infrared brazed at (d) 949°C for 600 s, (e) at 970°C for 600 s, (f) 1000°C for 1200 s; type III filler infrared brazed at (g) 949°C for 300 s, (h) 970°C for 600 s, (i) 1000°C for 1200 s.

joint. Both Cu and Ni stabilize the β -Ti, but under slow cooling conditions the β phase can transform to α plus another phase of compound.¹² The brazed joint then underwent another invariant reaction at 780°C upon cooling cycle of brazing^{11,13,14}:

Based on the Eq. (2), the consumption of Ti_2Cu and β -Ti yields Ti_2Ni and α -Ti.

Based on the previous study of infrared brazing Ti–6Al–4V and Nb using two clad Ti–Cu–Ni filler metals, the white phase illustrated in Fig. 4 is considered as mixture of Ti_2Cu and Ti_2Ni .^{11–13} It is worth mentioning that the white blocky region consists of different phases as marked by H and G in Fig. 4(g). The major difference between these two phases is Cu and Ni contents in the white region, and it needs further study. The presence of these intermetallic phases in the brazed joint is detrimental to the bonding strength of the joint.^{3,12} It is advised that the brazed joint is free of blocky Ti_2Ni and Ti_2Cu phases for obtaining a reliable joint.³

According to the Fig. 4, the amount of white intermetallic phase is rapidly decreased with increasing the brazing temperature due to higher depletion rate of Cu and Ni into the base metal, Ti-15-3. At higher brazing temperatures, both Cu and Ni atoms have sufficient mobility to overcome the activation energy barrier of diffusion, so the white intermetallic phase is disappeared rapidly. Similarly, time-dependent diffusive transport of both Cu and Ni from the joint into Ti-15-3 substrate is also found in the experiment. As a result, the amount of Ti_2Cu and Ti_2Ni is decreased with increasing the brazing temperature and time.

For all types of clad filler metals, the white intermetallic compounds are disappeared from the joint if the specimen is

brazed at 1 000°C for 1 200 s. For the joint infrared brazed at 970°C for 600 s, needle-like intermetallic phase is widely observed from the joint. Brazed joints using three different clad foils demonstrate similar microstructure. However, microstructures of these joints are different for the specimen infrared brazed at 949°C. The brazed joint using type III clad foil exhibits huge continuous white intermetallics. In contrast, the amount of white intermetallics significantly decreased for specimens using type I and II brazing foils.

For all brazing conditions used in the experiment, none of the brazing temperature exceeds the melting point of separate clad layer in the foil. The interdiffusion of Ti, Cu and Ni atoms occurred among the clad layers during brazing. Before the homogeneous molten braze is available during brazing, the clad brazing foil experiences interdiffusion, liquid formation and dissolution of the remaining clad foils. It is necessary that the interdiffusion stage is required if the clad layers contain pure elements, such as Cu and Ni layers in type III brazing foil. The initial liquid in the brazing foil is available only if Ti, Cu and Ni atoms are in contact. It takes time to form the initial liquid for the type III foil with pure element clad layers even if it contains 7 thin layers.

For the type II brazing foil with the clad sequence of Ti/50Cu–50Ni/Ti, a robust bond could not be obtained from the specimen infrared brazed at 949°C for 300 s. The brazed joint was debonded when it was cut by a slow speed diamond saw. Although the initial liquid in the brazing foil is readily available due to the contact among Ti, Cu and Ni atoms, the central initial liquid takes time to dissolve the outer Ti clad layer. The joint will be formed after the brazing foil is completely melted. Therefore, the specimen infrared brazed at 949°C for 600 s instead of 300 s is shown in Fig. 4(d).

As shown in Table 1, Cu–Ni alloys have been selected as the clad layers in making type I and II brazing foils. Once clad layers containing C713/Ti or 50Cu–50Ni/Ti are heated to the brazing temperature exceeding the eutectic temperature of clad brazing foil, the initial liquid is readily formed at the interfaces of C713/Ti and 50Cu–50Ni/Ti, respectively. The remaining clad layers are rapidly dissolved into the molten braze. The initial transient stage of forming the molten braze is rapid in using Cu–Ni alloy clad layers, because the interdiffusion stage of the brazing foil is not necessary. Redistribution of Cu and Ni in the braze alloy no longer depends upon solid-state interdiffusion only, so the depletion rate of Cu and Ni from the brazed joint into Ti-15-3 substrate is significantly enhanced in the early stage of brazing.

Figure 5 shows EPMA BEIs and chemical analysis results of SP-700 joint using three types of clad filler metals under various infrared brazing conditions. The microstructural evolution of infrared brazed SP-700 joint is very similar to that of infrared brazed Ti-15-3 joint. Type III foil also shows the slowest depletion rate of the white intermetallic phase because pure metal clad layers were applied in it. Higher depletion rate of Ti₂Cu and Ti₂Ni from the braze alloy into SP-700 substrate is observed as compared with that into Ti-15-3 substrate. The joint is almost free of white intermetallic phase for the specimen infrared brazed at 970°C for 600 s as illustrated in Figs. 5(b), 5(e) and 5(h). Additionally, the amount of white intermetallic phase in Fig. 5 is much less than that in Fig. 4 for the specimen infrared brazed at 949°C. It is deduced that alloying elements of the titanium alloy affect the depletion rate of both Cu and Ni from the joint into the substrate during brazing.

4. Conclusion

Microstructural evolution of infrared brazing Ti-15-3 and SP-700 using Ti–15Cu–15Ni foils with three types of clad layers is performed in the experiment, respectively. There is no significant difference among Cu–Ni alloy clad layers and

Fig. 5. EPMA BEIs and chemical analysis results of SP-700 joint using type I filler infrared brazed at (a) 949°C for 300 s, (b) 970°C for 600 s, (c) 1 000°C for 1 200 s; type II filler infrared brazed at (d) 949°C for 600 s, (e) at 970°C for 600 s, (f) 1 000°C for 1 200 s; type III filler infrared brazed at (g) 949°C for 300 s, (h) 970°C for 600 s, (i) 1 000°C for 1 200 s.

pure metal clad layers in brazing Ti alloys for the joint brazed above 970°C for 600 s. However, the use of Cu–Ni alloy clad layers in making Ti–15Cu–15Ni filler is helpful to obtain a joint free of blocky Ti₂Ni/Ti₂Cu intermetallics, especially for lower brazing temperature, e.g., 949°C. It is recommended to use the Cu–Ni alloy clad Ti–15Cu–15Ni foil in brazing the Ti alloy when the low brazing temperature is necessary.

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