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

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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 techniques in brazing Ti alloys due to their high bonding strength,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.9,10) It has been reported that the microstructural evolution of infrared 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.11) The melting behavior of clad Ti–15Cu–15Ni braze alloy 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 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 1000°C for 300 s, 600 s and 1200 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 μm.

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 μm 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 Ti/50Cu–50Ni/Ti. Type II foil consists of 7 clad layers of pure Cu, Ni and Ti with the sequence of Ni/Cu/Ni/Ti/Ni/Cu/Ni.

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

| Clad 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    |

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 1000°C for 300 s, 600 s and 1200 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 μm.

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 braze alloy 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 brazing foil.

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 μm, and it was much smaller than the phases identified. It is expected that EPMA analysis results provide acceptable accuracy in

Note
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 brazing:

$$\text{Ti}_2\text{Cu} + \beta\text{-Ti} = \text{Ti}_2\text{Ni} + \alpha\text{-Ti} \quad \text{(1)}$$

Accordingly, $\text{Ti}_2\text{Cu}$ and $\text{Ti}_2\text{Ni}$ are formed in the joint. Both Cu and Ni stabilize the $\beta$-Ti, but under slow cooling conditions the $\beta$ phase can transform to $\alpha$ plus another phase of compound. The brazed joint then underwent another invariant reaction at 780°C upon cooling cycle of brazing:

$$\text{Ti}_2\text{Cu} + \text{Ti}_2\text{Ni} = \text{Ti}_2\text{Ni} + \alpha\text{-Ti} \quad \text{(2)}$$

Based on the Eq. (2), the consumption of $\text{Ti}_2\text{Cu}$ and $\beta$-Ti yields $\text{Ti}_2\text{Ni}$ and $\alpha$-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 $\text{Ti}_2\text{Cu}$ and $\text{Ti}_2\text{Ni}$. 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. It is advised that the brazed joint is free of blocky $\text{Ti}_2\text{Ni}$ and $\text{Ti}_2\text{Cu}$ phases for obtaining a reliable joint.

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 $\text{Ti}_2\text{Cu}$ and $\text{Ti}_2\text{Ni}$ 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 homogenous 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 Ti 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 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.

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.

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