Transmission Electron Microscopy Study of Infrared Brazed Titanium Alloy Using Clad Ti–25Cu–15Ni Filler

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1. Introduction

The importance of brazing Ti alloys has been increased in past twenty years due to the strong demand from chemical and aerospace industry.1–9) SP-700 (Ti–4.5Al–3V–2Mo–2Fe in wt%) is a β-rich α–β titanium alloy, which can be strengthened by proper heat treatments.4) The brazing of Ti alloys using clad Ti–Cu–Ni filler metals has been extensively studied, and they are considered as one of the best choices in brazing Ti alloys due to their excellent bonding strength.5,6) The presence of Ti–Cu–Ni intermetallics in the brazed joint has a strong effect on the joint strength, and it needs further study.7)

The initial transient stage of brazing cannot be well analyzed in a traditional furnace brazing due to its slow thermal cycle. Infrared heating is characterized with a very high but well regulated heating rate that can reach up to 50°C/s.8) It has been proven to be a very powerful tool in investigating the microstructural evolution of brazed joint, especially for the very early stage of brazing. The purpose of this investigation is concentrated on transmission electron microscopy (TEM) study of the infrared brazed SP-700 alloy using Ti–25Cu–15Ni. Microstructure of the infrared brazed joint is examined in greater depth.

2. Experimental Procedures

Infrared vacuum brazing SP-700 alloy was performed at 970°C for 300 s and 1 800 s, respectively. Ti–25Cu–15Ni foil in wt% with the thickness of 50 μm was selected as the filler metal. The heating rate was set at 10°C/s, and all samples were preheated at 800°C for 300 s before heating up to the brazing temperature. The cross section of the brazed joint was examined using a JEOL JXA 8600SX electron probe microanalyzer (EPMA) equipped with the wavelength dispersive spectroscopy (WDS). The acceleration voltage was 15 kV, and its minimum spot size was 1 μm. For the detailed microstructural observation, TEM specimens were sectioned in thin slices within various brazed zones of the joint. Thin foils were prepared by a standard jet-polisher using an electrolyte of 6% HClO4, 30% C2H5OH and 64% CH3COOH at room temperature. The operation voltage is 30 V, and the current is 40–50 mA.

3. Results and Discussion

Figure 1 shows EPMA backscattered electron images (BEIs) and WDS chemical analysis results of SP-700 joint using clad Ti–25Cu–15Ni filler infrared brazed at 970°C for 300 s and 1 800 s, respectively. It is obvious that microstructures of brazed joints are strongly related to the infrared brazing time. For the 300 brazed specimen, blocky Ti2Cu is widely observed in the brazed zone as marked by A in Fig. 1(b). In addition to Ti2Cu, the Ti-rich matrix is also found as marked by B and C in Figs. 1(a) and 1(b). The blocky Ti2Cu is completely disappeared from the joint for the 1 800 s brazed specimen and there is only Ti-rich matrix left in the brazed zone as marked by D and E in Fig. 1(c). The Ti-rich matrix cannot be accurately identified via EPMA observation even using higher magnification as illustrated in Fig. 1(d).

The chemical composition of Ti–25Cu–15Ni brazing foil in at% is Ti–20.7Cu–13.4Ni. Based on the related binary alloy phase diagrams, the maximum solubility of Cu and Ni in the β-Ti is 13.5 at% and 10 at%, respectively.9) The disappearance of blocky Ti2Cu in the 1 800 s brazed joint is primarily attributed to high solubility of Cu in the β-Ti. Both dissolution of SP-700 substrate into the molten braze and diffusion of Cu into SP-700 substrate result in depletion of Cu from the brazed zone during infrared brazing. Therefore, the depletion of Cu strongly depends on the brazing condition. Longer infrared brazing time such as 1 800 s results in the infrared brazed joint free of blocky Ti2Cu, and Ti-rich phase dominates the brazed joint as illustrated in Figs. 1(c) and 1(d). The transformation of β-Ti
in the brazed zone upon cooling cycle of brazing is strongly related to its chemical composition and cooling rate. The average cooling rate between 970°C and 600°C during infrared brazing is 1.5°C/s. It is also noted that both Cu and Ni contents in region I (marked by D) are more than those in region II (marked by E) as shown in Fig. 1(c). Accordingly, separate TEM examinations of these two regions are performed in the experiment.

**Figure 2** shows TEM micrographs and EDS chemical analysis results of region I in Fig. 1(c) infrared brazed at 970°C for 1 800 s: (a, b) BF images of fine eutectoid, (c) BF image of acicular α-Ti and retained β-Ti, (d) SADP of the acicular α-Ti with the zone axis of [1211].

![Fig. 2](image)

**Fig. 2.** TEM micrographs and EDS chemical analysis results of region I in Fig. 1(c) infrared brazed at 970°C for 1 800 s: (a, b) BF images of fine eutectoid, (c) BF image of acicular α-Ti and retained β-Ti, (d) SADP of the acicular α-Ti with the zone axis of [1211].

The depletion of Cu and Ni from the molten braze into SP-700 substrate is not prominent for the brazed joint with a short brazing cycle such as 300 s. Because the Cu content of the braze alloy greatly exceeds the maximum solubility of Cu in the β-Ti during infrared brazing, coarse primary Ti2Cu are readily formed during brazing as illustrated in Figs. 1(a) and 1(b). It is also worth mentioning that low Ni content of the braze alloy and high solubility (up to 15 at%) of Ni in Ti2Cu result in the brazed joint free of Ti2Ni intermetallic compound in the experiment.10,11)

In addition to the blocky Ti2Cu in region III, the Ti-rich matrix is alloyed with 4.2% Al, 4.4% Cu, 1.7% Fe, 0.4% Mo, 5.5% Ni and 1.9% V as marked by B in Fig. 1(b). **Figure 4** shows TEM micrographs of region III in Fig. 1(a). The Ti-rich matrix of region III consists of retained β-Ti (marked by D) and non-lamellar eutectoid Ti2Cu (marked...
by A and B) as well as α-Ti (marked by C) as illustrated in Fig. 4(a). It is noted that the size of non-lamellar eutectoid shown in Fig. 4(a) is much larger than that of lamellar eutectoid displayed in Fig. 2(a). Figure 4(b) shows the DF image using a (110) retained β-Ti spot. The retained β-Ti is alloyed with many β-stabilizers such as Cu, Fe, Mo, Ni and V resulting from the partition of β-Ti decomposition upon cooling cycle of brazing. In contrast, the eutectoid α-Ti is alloyed with very limited β-stabilizers.

4. Conclusion

Transmission electron microscopy study of the infrared brazed SP-700 alloy using Ti-25Cu-15Ni has been performed in the experiment. The 300 s brazed joint consists of blocky Ti2Cu and transformed β-Ti. The transformed β-Ti is comprised of retained β-Ti, non-lamellar eutectoid Ti2Cu and α-Ti. Increasing the brazing time to 1 800 s causes depletion of Cu and Ni contents from the braze alloy into SP-700 substrate, so the coarse Ti2Cu is disappeared from the brazed zone. The β-Ti alloyed with Cu proceeds eutectoid transformation upon cooling cycle of brazing. Nano-sized lamellar eutectoid α-Ti and Ti2Cu are widely observed in the brazed joint. Further depleting the Cu content of the brazed zone results in decreasing the amount of eutectoid α-Ti and Ti2Cu. The transformed β-Ti matrix mainly consists of acicular α-Ti and retained β-Ti. Transformations of the infrared brazed joint are summarized in Table 1.

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