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Microstructural evolution of infrared brazed Ti-15-3 alloy using Ti-15Cu-15Ni and Ti-15Cu-25Ni fillers

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Abstract

Microstructural evaluations of the infrared brazed Ti-15-3 alloy have been performed on as-brazed and post-brazing annealed samples. Microstructures of as-brazed joints consist of a Ti-rich phase alloyed with higher Cu and Ni content, a Ti-rich phase with lower Cu and Ni, and eutectoid two-phase structures. Post-brazing annealing modified the joint microstructure and the resulting microstructures depend on the filler composition, annealing temperature and time. Appropriate brazing process cycles can be developed to reduce or eliminate the presence of residual Cu–Ni rich Ti phase in the brazed joints using Ti–Cu–Ni filler metals. © 2005 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

Keywords: Brazing; SEM; Titanium alloys; Interfaces

1. Introduction

Ti-15-3 is a metastable beta titanium alloy that was developed to reduce strip processing costs due to its excellent forming characteristics at room temperature [1]. The nominal composition of Ti-15-3 alloy, in weight percent, is 15%V, 3%Cr, 3%Al, 3%Sn with the balance being titanium [2–4]. Ti-15-3 alloy is capable of developing very high tensile strength, of around 1250 MPa, if proper thermomechanical treatments are used. The strengthening mechanism of Ti-15-3 is attributed to the precipitation of uniformly dispersed fine α phase in the β -matrix.

Brazing of titanium and its alloys has become increasingly important during the past decade because of increasingly demanding structural applications [5,6]. Brazing of Ti alloys is complicated due to the nature of the materials. Titanium is a highly reactive element, on which non-wetting scale is readily generated when exposed to elevated temperatures. Ti reacts readily with many elements to form brittle intermetallics. Titanium-based brazing alloys, such as Ti–Cu–Ni and Ti–Zr–Cu–Ni, have been considered to be the best choice for the brazed joint to operate at high temperatures and in corrosive environments [7,8]. Cu and Ni are necessary melting point depressants in the brazing fillers. However, the effects of these elements on the microstructural development and joint strength have not been adequately studied in order to optimize the brazing process variables.

Infrared heating is a very useful tool in evaluating the microstructural development of brazed joints. The high heating rate (up to 3000 °C/min) and controlled environment in an infrared furnace are useful to study the effect of process variables on the microstructural development from brazing. It has been successfully applied in several studies on brazing various alloy systems [9–12]. This investigation is focused on applying infrared heating to the vacuum brazing of Ti-15-3 alloy using two Ti–Cu–Ni filler metals. Post-brazing annealing at various time periods and temperatures was applied to the brazed samples to characterize the development of microstructures in order to identify the effects of process variables.

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2. Experimental procedures

Ti-15-3 plates measuring $10 \times 7 \times 3$ mm were prepared for the brazing experiments. Mating surfaces were polished and degreased in an ultrasonic bath of acetone prior to the infrared brazing. Ti–15Cu–15Ni and Ti–15Cu–25Ni foils at 50 µm thick were used as the brazing fillers. The brazing filler foils consisted of Ti, Cu and Ni layers in the as-rolled condition [13]. The liquidus temperatures of Ti–15Cu–15Ni and Ti–15Cu–25Ni foils are 950 and 914 °C, respectively [5,13].

Infrared brazing was performed in a vacuum of 5×10^{-5} mbar at 970 °C for 300 s with a constant heating rate of 600 °C/min. An isothermal hold at 800 °C for 600 s prior to the final ramp to brazing temperature was included in the brazing cycle to minimize the potential temperature gradient. Infrared brazed specimens were post-brazing annealed at 900 °C and 750 °C for various time periods, which are summarized in Table 1.

The brazed specimen was sectioned by a low speed diamond saw, and prepared by the standard metallographic procedure for microstructural examination. Kroll's reagent (3 ml HF, 6 ml HNO₃ and 100 ml H₂O) was selected as the etching solution. The cross section of the brazed specimen

Table 1	
Summary of annealing conditions used in the experiment	

Filler metal (wt.%)	Annealing temperature (°C)	Annealing time (h)		
Ti–15Cu–15Ni	900 750	1, 4, 12 5, 15, 50, 150		
Ti–15Cu–25Ni	900 750	1, 4, 12 5, 15, 50, 150		

All specimens are infrared brazed at 970 °C for 300 s.

was examined using a Hitachi 3500H scanning electron microscope (SEM) operated at an accelerating voltage of 15 kV. Semi-quantitative chemical analysis was performed using an energy dispersive spectroscopy (EDS) with an operation voltage of 20 kV and a spot size of 1 μ m.

3. Results and discussion

As-brazed microstructures of Ti–15Cu–15Ni filler are shown in an SEM backscattering electron image (BEI) (Fig. 1(a)) and a secondary electron image (SEI) (Fig. 1(b)) at a higher magnification. The brazed joint consists of: (1) Ti-rich phase with higher Cu, Ni contents (marked by A), (2) Ti-rich phase with lower contents of



Fig. 1. SEM images and EDS chemical analysis results in atomic percent of infrared brazed Ti-15-3 specimens at 970 °C for 300 s using Ti-15Cu-15Ni braze alloy: (a) BEI, (b) SEI, as infrared brazed, (c) BEI, (d) SEI, annealed at 900 °C for 1 h and (e,f) SEI, annealed at 900 °C for 12 h.

Cu and Ni (marked by D), (3) eutectoid region (marked by B and C).

Cu–Ti and Ni–Ti binary phase diagrams [14] are shown in Fig. 2 to facilitate the description of the microstructural development in the brazed joints. The chemical composition of the Ti–15Cu–15Ni brazed alloy in atomic percent is 74.8%Ti, 12.1%Cu and 13.1%Ni. Both Cu and Ni are β stabilizers in Ti alloys, and belong to a family of the β eutectoid system, of which the β phase transforms to an alpha plus Ti₂Cu or Ti₂Ni structure under the slow cooling



Fig. 2. Binary alloy phase diagrams: (a) Cu-Ti and (b) Ni-Ti [14].



Location	Ti	V	Cr	Al	Sn	Cu	Ni
А	74.1	0.9	0.6	0.7	0.3	10.2	13.2
В	79.3	7.0	1.4	5.1	1.0	3.6	2.6
С	72.8	1.0	0.9	1.5	0.3	4.5	19.0
D	79.4	6.3	1.7	5.2	0.9	3.6	2.9
E	69.5	1.5	1.5	0.6	0.2	6.9	19.8
F	79.3	7.8	1.6	5.2	0.9	3.0	2.2
G	77.3	9.2	2.6	3.1	1.8	4.3	1.7

Fig. 3. SEM images of infrared brazed Ti-15-3 specimens at 970 °C for 300 s using Ti-15Cu-15Ni braze alloy: (a,b) BEIs, annealed at 750 °C for 5 h, (c) BEI, annealed at 750 °C for 5 h, (e) SEI and (f) BEI, annealed at 750 °C for 15 h.

condition [1,2]. The result of this eutectoid phase transformation is mostly observed along the interfaces between the brazed joint and the Ti-15-3 substrate, as illustrated in Fig. 1(a) and (b).

Diffusive transport of Cu and Ni from the brazed joint into the substrate is driven by the concentration gradient. The phase diagrams of Cu–Ti and Ni–Ti show that the solubility of Cu and Ni in the β -Ti is much greater than that in the α -Ti. The concentration gradients of Ni and Cu in the brazed alloy provided the driving force to the dissolution of Cu and Ni from the brazed alloy into the β Ti-15-3 alloy promoted the formation of eutectoid structure along the interface between the brazed alloy and substrate. After a post-brazing anneal at 900 °C for 1 h, the microstructure of the brazed joint changed significantly (Fig. 1(c) and (d)). The complex solidification structures in the as-brazed joint transformed into a β -Ti matrix that contains a network of fine eutectoid, which is probably the remnants of the Ti–Cu–Ni filler alloy from solidification.

The addition of vanadium in the titanium alloy is categorized as a β isomorphous system in which the alloying element is completely miscible in the β phase, and the decomposition of β phase does not occur [1,2]. The amount of V in the brazed joint is crucial in controlling the decomposition of β phase upon cooling. The complex microstructures produced in the as-brazed condition, which consist of eutectoid phase, are gradually transformed to that of a β -Ti matrix containing minor eutectoid structure as demonstrated in Fig. 1(c) and (d) after the application of a post-brazing anneal.

The brazed alloy is enriched with Cu and Ni while the Ti-15-3 alloy contains V and Cr as the major alloying elements. The homogenization of V, Cr, Cu and Ni in the brazed joint and adjacent area during the post-brazing anneal is unavoidable. The depletion of Cu and Ni in the brazed joint resulted in the disappearance of the Cu-Ni rich Ti phase, while the increasing V content in the brazed joint stabilizes the beta titanium. The combined effects cause the diminishing of the complex as-brazed microstructure while the β -Ti, which was stabilized by the presence of V, Cu, Ni, became the dominating feature in the specimen annealed at 900 °C for 12 h (Fig. 1(e) and (f)). The features of the annealed joint, with a high vanadium and low copper and nickel content, are represented by the composition of area G. The homogenization of V, Cr, Cu and Ni amongst the brazed joint and the Ti-15-5 matrix is shown



Fig. 4. SEM BEIs and EDS chemical analysis results in atomic percent of infrared brazed Ti-15-3 at 970 °C for 300 s using Ti-15Cu-25Ni braze alloy: (a) BEI, (b) SEI, as infrared brazed, (c) BEI, (d) SEI, annealed at 900 °C for 1 h and (e,f) SEIs, annealed at 900 °C for 12 h.

by Fig. 1(e), which was taken at low magnification to include the widened joint area affected by the redistribution of these elements.

Fig. 3 displays SEM images of infrared brazed Ti-15-3 specimens given a post-braze anneal at 750 °C for 5, 15, 50 and 150 h, respectively. The EDS chemical analysis results (in atomic percent) are included to show the stability of the Ti–Cu–Ni phase as well as the effect of a lowered annealing temperature on the homogenization of the brazed joint, although the amount of Cu–Ni rich Ti phase decreased with increasing annealing time. Cu–Ti rich Ti phase only completely disappeared in the specimen annealed for 150 h. As compared with specimens annealed at 900 °C, the rate of Cu–Ni rich Ti phase depletion is significantly slower for specimens annealed at 750 °C. The difference in homogenization rate might be due to the lower diffusion rate of V, Cu and Ni in Ti at the lower annealing temperature.

Fig. 4(a) and (b) display the cross section of the joint infrared brazed at 970 °C for 300 s using Ti–15Cu–25Ni as the filler metal. The chemical composition of the Ti–15Cu–25Ni filler metal in atomic percent is 12.3%Cu, 22.2%Ni and balance Ti. It is obvious that the Cu–Ni rich

Ti phase dominates the entire brazed joint as marked by A and C in Fig. 4(a). A coarse eutectoid microstructure is observed at the interface between Ti-15-3 and Cu–Ni rich Ti phase as marked by D in Fig. 4(b). Similar to the aforementioned results for Ti–15Cu–15Ni brazed joints, the Cu– Ni rich Ti phase in the Ti–15Cu–25Ni brazed joints, marked by E in Fig. 4(d), is greatly reduced for the specimen given a post-brazing anneal at 900 °C for 1 h albeit presented at higher volume. Both the eutectoid and Cu– Ni rich Ti phases are replaced by a single Ti-rich phase with high V and low Cu and Ni contents, as marked by G in Fig. 4(f), when the post-brazing anneal was extended to 12 h. It resulted from interdiffusion between Ti-15-3 and the brazed alloy during annealing of the brazed joint.

Fig. 5 shows the SEM micrographs and EDS chemical analysis results (in atomic percent) for infrared brazed joints using Ti–15Cu–25Ni, which were given the post-brazing anneal at 750 °C for 5, 50 and 150 h, respectively. The Cu–Ni rich Ti phase, marked by A, B, E and G, persisted in the brazed joints even at the longest annealing time and featured with low V contents. The post-brazing anneal is effective in reducing the Cu–Ni rich Ti phase with increasing annealing time, and the amount of V-rich matrix



Fig. 5. SEM BEIs and EDS chemical analysis results in atomic percent of the infrared brazed Ti-15-3 at 970 °C for 300 s using Ti-15Cu-25Ni braze alloy annealed at 750 °C: (a,b) 5 h, (c,d) 50 h and (e,f) 150 h.

(marked by C, F and H) is increased, as shown in Fig. 5(a), (c) and (e). Similarly, the Ti-rich matrix is characterized with high V and low Ni contents. However, the Cu–Ni rich Ti phase cannot be completely removed, even when annealed at 750 °C for 150 h. Both higher Ni content in the Ti–15Cu–25Ni brazing alloy and the lower post-brazing anneal temperature contribute to the persistent presence of un-dissolved Cu–Ni rich Ti phase in the brazed joint.

4. Conclusions

Microstructural observations of infrared brazed Ti-15-3 using Ti-15Cu-15Ni and Ti-15Cu-25Ni brazing filler foils have been examined. Post-brazing anneal was applied to the brazed joints to characterize the effect of annealing time and temperature on the microstructure of the joints. The as-braze microstructure consists of at least three distinctive phases, a Ti-rich phase alloyed with higher Cu and Ni content, a Ti-rich phase alloyed with lower content of Cu and Ni, while the eutectoid structure are also presented. The micro-chemical analyses on the as-brazed and annealed samples showed that the redistribution of V, Cr, Cu and Ni dictated the microstructural evolution in the brazed joint. Depletion of Cu and Ni in the brazed joint results in the dissolution of Cu-Ni rich Ti phase, and the increasing V content in the brazed joint stabilized the beta titanium. The specimen annealed at 900 °C shows a significantly higher rate of Cu-Ni rich Ti phase dissolution than that of the specimen annealed at 750 °C. Diffusion rates and the solubility of alloying elements in Ti are both temperature dependent variables. Additional post-brazing annealing is needed to establish the relative merits of diffusion and solubility. The Cu-Ni rich Ti phase in the Ti-15Cu–25Ni brazed joint is much more persistent than that in the Ti–15Cu–15Ni brazed joint. Although post-brazing annealing at 900 °C is effective to homogenize the microstructure of the brazed joint, the lower liquidus temperature of Ti–15Cu–25Ni might not be as useful to braze Ti alloys.

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