



Characterization of Titanium/Steel Joints Brazed in Vacuum

Copper-based brazing filler metal can be used for brazing titanium to steel

BY A. EL REFAEY AND W. TILLMANN

ABSTRACT. Furnace brazing was carried out to produce joints between commercially pure titanium and low-carbon steel using copper-based filler metal (Cu-12Mn-2Ni) in the temperature range of 930° to 1000°C (1706° to 1832°F). The microstructures of the transition joints were revealed in optical and scanning electron microscopy (SEM). The study depicts the presence of different reaction layers in the brazed area, and their chemical compositions were determined by energy dispersive spectroscopy. The occurrence of different intermetallic compositions such as FeTi and Fe₂Ti has been predicted from the chemical analyses and confirmed by x-ray diffraction technique. The maximum shear strength of 61 MPa (8.8 ksi) was obtained for the couple bonded at 1000°C (1832°F) due to better coalescence of the mating surfaces. At a lower joining temperature of 930°C (1706°F), the bond strength is also lower due to incomplete coalescence of the mating surfaces.

Introduction

Titanium offers an excellent combination of mechanical properties and corrosion resistance. These features have led to the extensive use of titanium and its alloys in various industrial sectors. The major disadvantages of this metal are its high cost and difficulty in joining it with other materials. Among the methods for overcoming these disadvantages is joining titanium to steel. These joints, if successfully made, possess all the requirements for high-quality joints, and also reduce the amount of materials needed, thus making

them economically attractive and viable.

A review of the existing literature reveals that diffusion welding has been used successfully in joining titanium to steel alloys. However, the great care required in the surface-preparation stage and the impracticality of this method for mass production have limited the use of this process (Refs. 1–5). Explosion welding has also been used to clad titanium to steel alloys in many applications (Refs. 6–8). Although brazing is one of the most common and simplest joining processes for dissimilar metals (Refs. 9, 10), to the best of our knowledge, only data on microstructure investigation on brazing titanium to stainless steel have been reported (Refs. 11, 12).

In the case of brazing titanium to steel, the chemical compositions of the brazing filler metal and the brazing atmosphere are very important. Many kinds of brazing filler metals for titanium and titanium alloys had been studied such as Ag-based, Al-based, Ti-based, and Cu-based brazing filler metals (Refs. 13–17). On the other hand, although filler metals other than copper have been used in the brazing of low-alloy steel assemblies, copper is generally preferred because of its low cost and the high strength of the produced joints (Ref. 18). In this study, Cu-12Mn-2Ni was chosen as the brazing filler metal because it provides good chemical compatibility in

fusion reaction applications, and has good wettability to many materials. Furthermore, it is suggested that the higher percentage of Mn was responsible for the additional improvement of its wettability, and it is not expensive compared to most of the other filler alloys.

The brazing of titanium to steel can be carried out using a vacuum furnace or induction heating within a vacuum system. The advantage of induction heating is that the entire assembly does not need to be heated, and the throughput time is quicker. However, it is only suitable for a few particular configurations of components, such as ducts and fittings. In the majority of the cases in which complicated components are to be joined, a vacuum furnace has always been the choice (Ref. 19).

The objective of this investigation was to focus on the brazing of commercially pure titanium plate to a low-carbon steel plate by using a vacuum furnace at various brazing temperatures to investigate the effects of the brazing temperature on the joint strength and microstructure.

Experimental Method

The commercially pure titanium and the low-carbon steel (0.12 C, wt-%) plate were in the form of 2-mm (0.079-in.) plates. The plates were cut into 125- × 28-mm (4.921- × 1.102-in.) chips for shear strength testing and 10- × 10-mm (0.394- × 0.394-in.) chips for microstructure analysis. These specimens were then subjected to several stages of grinding papers up to 1000 grit, and subsequently, ultrasonically cleaned in acetone before brazing. The filler metal was a 100 μm (0.004 in.) Cu-12Mn-2Ni (wt-%) foil, and its melting range was 970° to 990°C (1778° to 1814°F). The brazing foil was cleaned in

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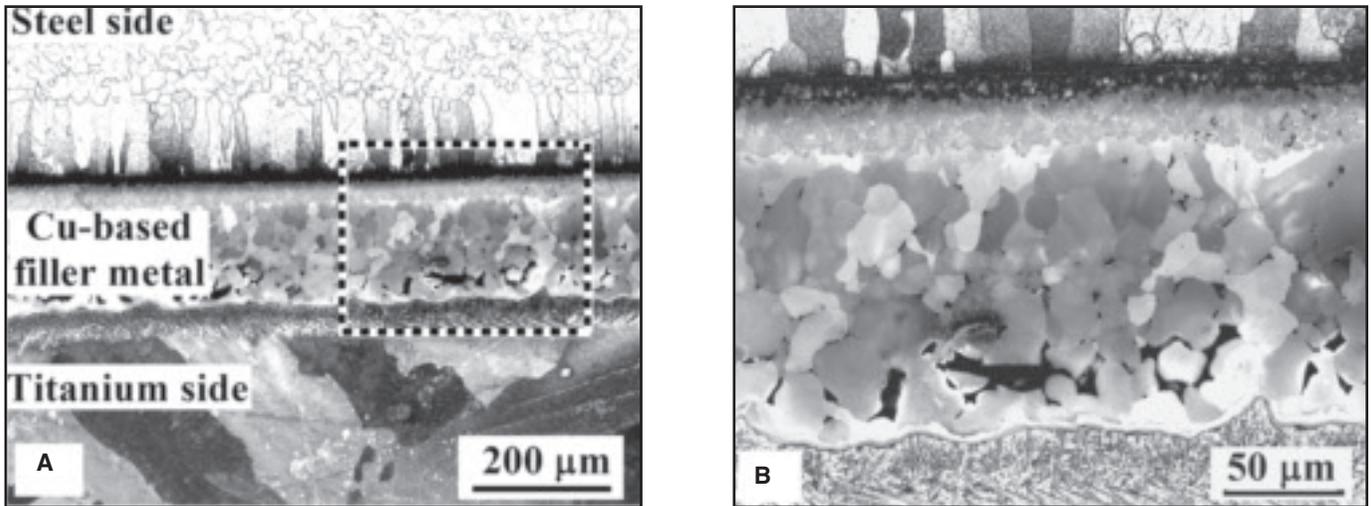


Fig. 1 — Microstructure of the joint brazed at 930°C (1706°F). A — General view of the microstructure; B — enlarged view of the brazed area.

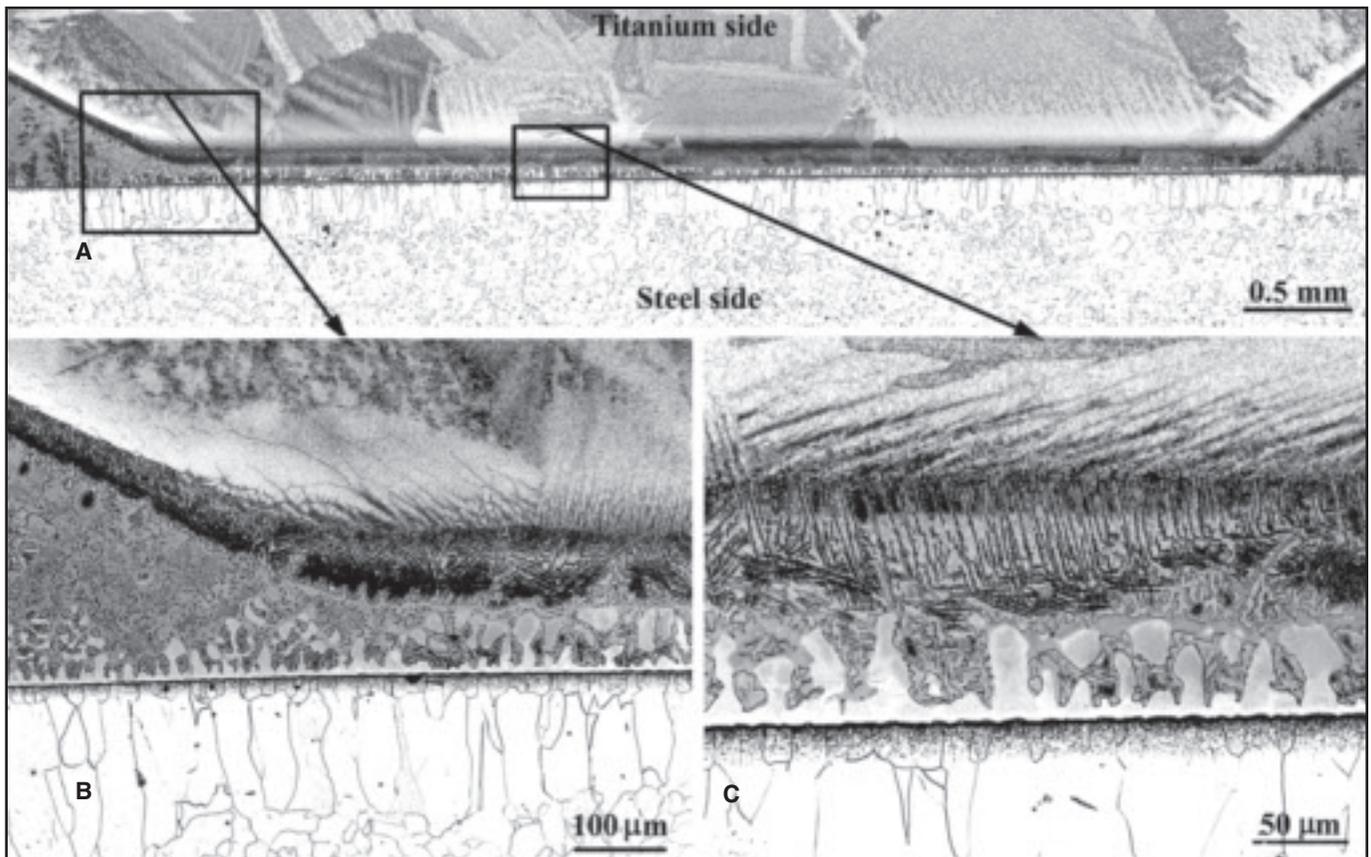


Fig. 2 — Microstructure of the joint brazed at 1000°C (1832°F). A — General view of the brazed joint; B — enlarged view of the fillet of the joint; C — enlarged view on the middle area of the joint.

acetone before brazing and then sandwiched between the overlapped areas of the base metal.

After adjusting the overlap width to 6 mm (0.236 in.) (three times the thickness of base metal), the joints were fixed with a stainless steel clamp, and then carefully placed into the vacuum furnace. Brazing experiments were carried out between 930°

and 1000°C (1706° and 1832°F) to study the effect of the brazing temperature on the metallurgical and mechanical properties of the joint. Brazing experiments were carried out for 15 min at a pressure of 2×10^{-5} Pa (2.9×10^{-9} lb/in.²). The heating and cooling rates were adjusted at 15°C/min (59°F/min).

The cross sections of the bonded titanium/steel joints were prepared for metal-

lographic analysis by standard polishing techniques and then etched by 5% HF, 20% HNO₃, and 75% glycerol solution for 60 s for titanium side, and by 3% Nital solution for the steel side. The microstructures were investigated by optical and scanning electron microscopes. Moreover, X-ray diffraction (XRD) analyses were carried out with the help of diffractometer to identify the

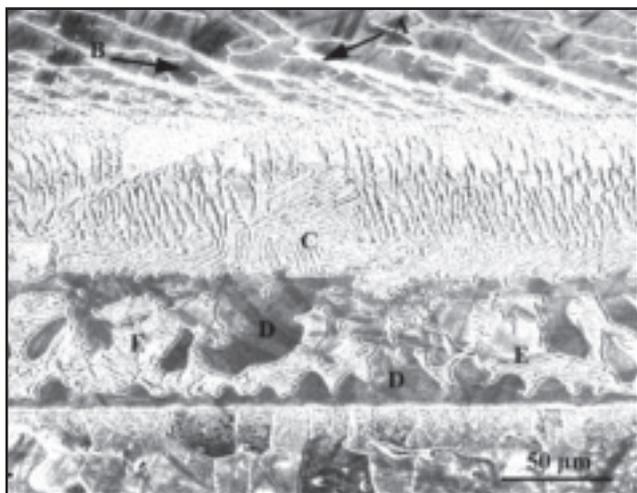


Fig. 3 — SEM image of the brazed joints at temperatures of 1000°C (1832°F).

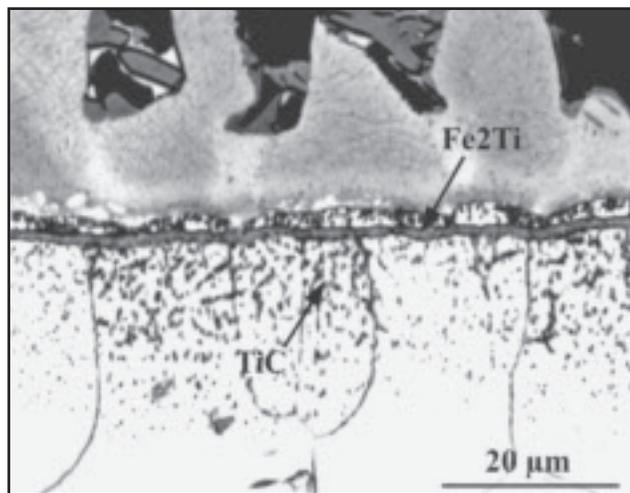


Fig. 4 — Microstructure at steel/copper interfacial area at a brazing temperature of 1000°C (1832°F).

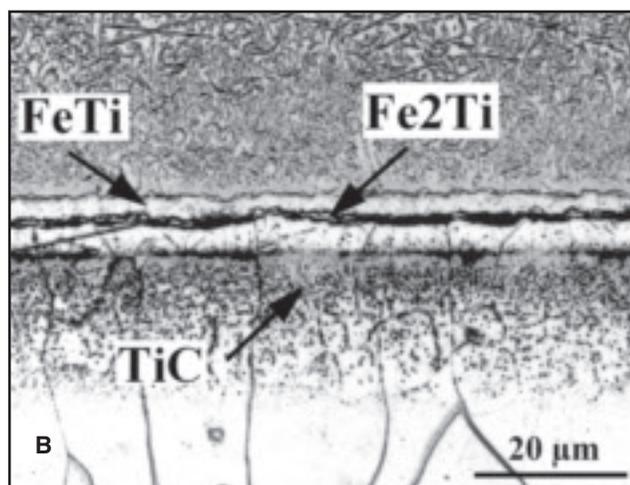
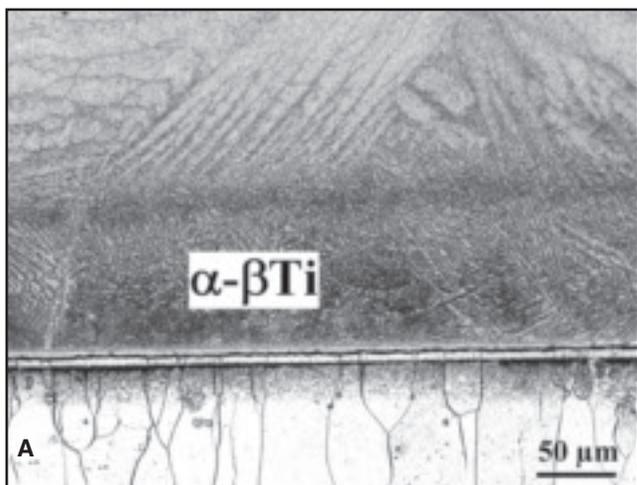


Fig. 5 — Microstructure of the joint brazed at 970°C (1778°F). A — General view of the microstructure; B — enlarged view on the steel/copper interfacial area.

phases formed on joint fracture surfaces after having performed the shear test. Cu, K_α, and Ni were chosen as X-ray source and filter for the analysis.

The hardness measurement was performed with the help of a Vickers hardness testing machine with 25-s impressing time. Shear specimens were machined out in accordance to AWS C3.1-63 (standard test for brazed joints). The test was performed at room temperature, and the displacement speed was 0.5 mm/s (0.02 in./s).

Results and Discussion

Microstructure of Joints

The brazing filler metal could not be melted completely at a brazing temperature of 930°C (1706°F), especially at the middle of the brazed joint, compared to the areas in contact with titanium and

steel substrates, which showed melting and interaction of the brazed alloy with the two base metals, as it is shown in Fig. 1. This is attributed to the mutual diffusion and dissolving of elements from base metals into the brazing filler metal and vice versa, which lowers the melting temperature of this area compared to the bulk of brazing filler metal.

Figure 2 shows a typical microstructure appearance of the specimen brazed at a temperature of 1000°C (1832°F) for 15 min. It is clear that a sound joint was obtained since a homogeneous microstructure without voids or cracks was observed along the joint, as it is shown in Fig. 2A. According to the Cu-Ti binary phase diagram, copper plays the role of a melting point depressant for the titanium alloy since it diffuses readily in titanium, lowers its melting point, and dissolution of titanium substrate took place as is clearly shown in the fillets, which

formed at both sides of the joint — Fig. 2B. Several interaction layers occur between the copper-based brazing alloy and the two substrates, as shown in Fig. 2C. The steel/copper bonding interface is planar in nature, and a thin diffusion black layer was revealed at the interface area. Columnar structure resulted from generation of a ferrite phase in the vicinity of the interface by the diffusion of the ferrite-stabilizing Ti el-

Table 1 — Chemical Analysis at Areas Shown in Fig. 3

Region	Average chemical analyses, at.-%			
	Ti	Fe	Cu	Mn
A	87.80	4.32	6.25	1.63
B	99.97	0.03	—	—
C	73.36	7.85	16.34	2.45
D	48.96	16.65	31.72	2.68
E	71.91	9.26	15.49	3.34

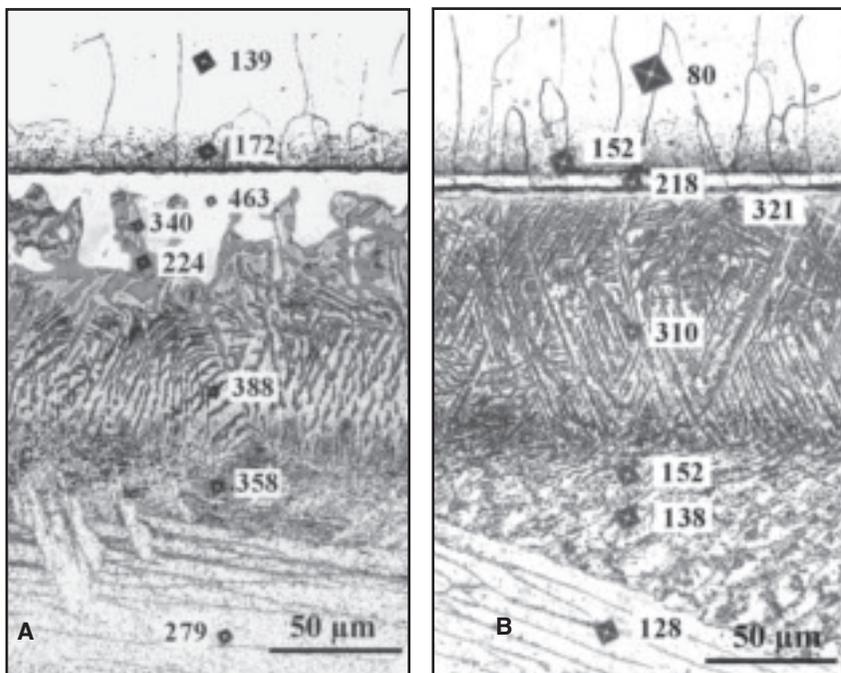


Fig. 6 — Hardness distribution along the brazed joints. A — Joint brazed at 1000°C (1832°F); B — joint brazed at 970°C (1778°F).

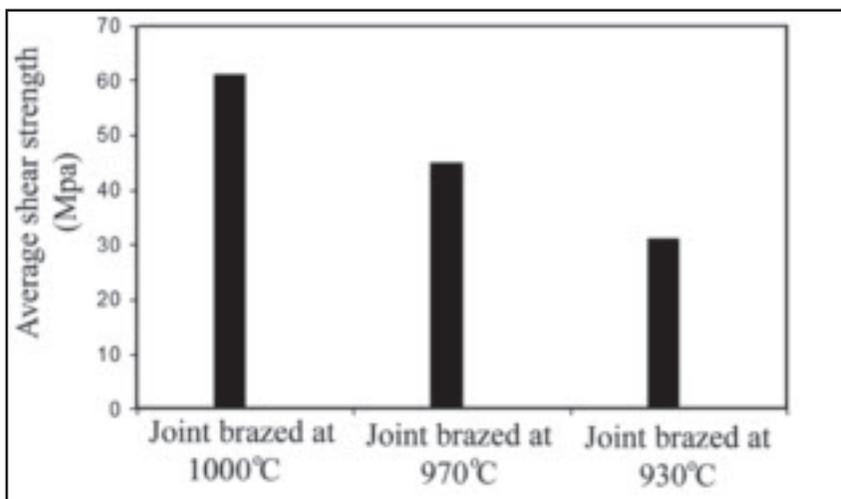


Fig. 7 — The average shear strengths of the joints at different brazing temperatures.

ement into the steel, which is located in the austenite state at the holding temperatures. In general, the formation of ferrite in an austenite matrix is important in the case of steels, which exhibited columnar grains (Ref. 20). On the other hand, the grains of titanium showed excessive grain growth after recrystallization as shown in Fig. 2A.

Figure 3 shows a SEM image of the transition joints at a brazing temperature of 1000°C (1832°F). Moreover, results of chemical analyses for the different areas are listed in Table 1. It is worth noting that the migration of Cu, Fe, and Mn (strong β -stabilizing elements) in the titanium substrate lowers the eutectoid transformation

temperature of Ti and α - β phase aggregate forms by the decomposition of β -Ti during cooling (Refs. 21, 22). The β -Ti phase is shown by region A in Fig. 3. The β -Ti forms as bright needles while the α -Ti forms as dark platelike structure between the needles of β -Ti (region B). The β -Ti showed high content of Cu and Fe in comparison to α -Ti, since the solubility of Cu and Fe in β -Ti is much higher than α -Ti, as it is indicated in the Ti-Cu and Ti-Fe phase diagrams (Ref. 23). The composition of region C in Fig. 3 shows that this is the β -Ti phase, which is enriched by more content of Fe and Cu. Based on the chemical analysis of area D, it is expected to

contain FeTi + Cu intermetallic phase (FeTi). According to Van Beek et al., the Fe-Ti-Cu ternary alloy phase diagram suggests that nearly 38 at.-% Cu could be dissolved in FeTi (Ref. 24) while the irregular phase, which is represented by the area E, is a phase mixture of α - β Ti.

Because of the high percentage of titanium, which reached the steel interfacial area with the copper brazed alloy, titanium reacted with the steel substrate and formed a continuous reaction layer as it is shown in Fig. 4. It was determined by compositional analysis that this layer was a reaction layer consisting of Fe₂Ti. On the other hand, close to the Fe₂Ti phase at the steel side, a ferrite structure containing TiC particles was detected. The formation of this region provides evidence for the diffusion of Ti into the steel.

The microstructure features of a titanium/steel brazed joint at 970°C (1778°F) are shown in Fig. 5A. Similar to the brazed joint at a temperature of 1000°C (1832°F), the microstructure showed a mixture of α - β Ti in the brazed zone, Fe₂Ti, and TiC at the interfacial area. Meanwhile, the FeTi phase formed as a thin layer, probably owing to the lower diffusion rate of Fe into the brazing alloy at a brazing temperature of 970°C (1778°F). Figure 5B provides an enlarged view on the steel/copper interfacial area.

Mechanical Properties of Joints

The hardness distribution along the joints brazed at temperatures of 1000°C (1832°F) and 970°C (1778°F) is shown in Fig. 6A and B, respectively. Because of the formation of the FeTi phase at the steel/copper interfacial area, this layer presented the highest value of hardness in all joints and consequently, it is brittle and constitutes the most detrimental phase in the microstructure. The mixed structure of α - β Ti at both brazing temperatures also showed a high hardness level owing to the high solubility of Fe, Cu, and Mn in β -Ti phase. Moreover, owing to the formation of Fe₂Ti and TiC at the steel interfacial area to the brazed alloy, hardness values of this area were higher than the steel base metal.

Figure 7 represents the average shear strengths of the joints at different brazing temperatures. The average shear strength of the joint showed the highest value (61 MPa or 8.8 Ksi) at a brazing temperature of 1000°C (1832°F) compared to joints brazed at 970°C (1778°F) and 930°C (1706°F). It was expected that the joint brazed at a temperature of 970°C (1778°F) achieves higher shear strength than the joint brazed at 1000°C (1832°F) due to the low thickness of FeTi phase which, as mentioned before, represents the most detrimental phase in

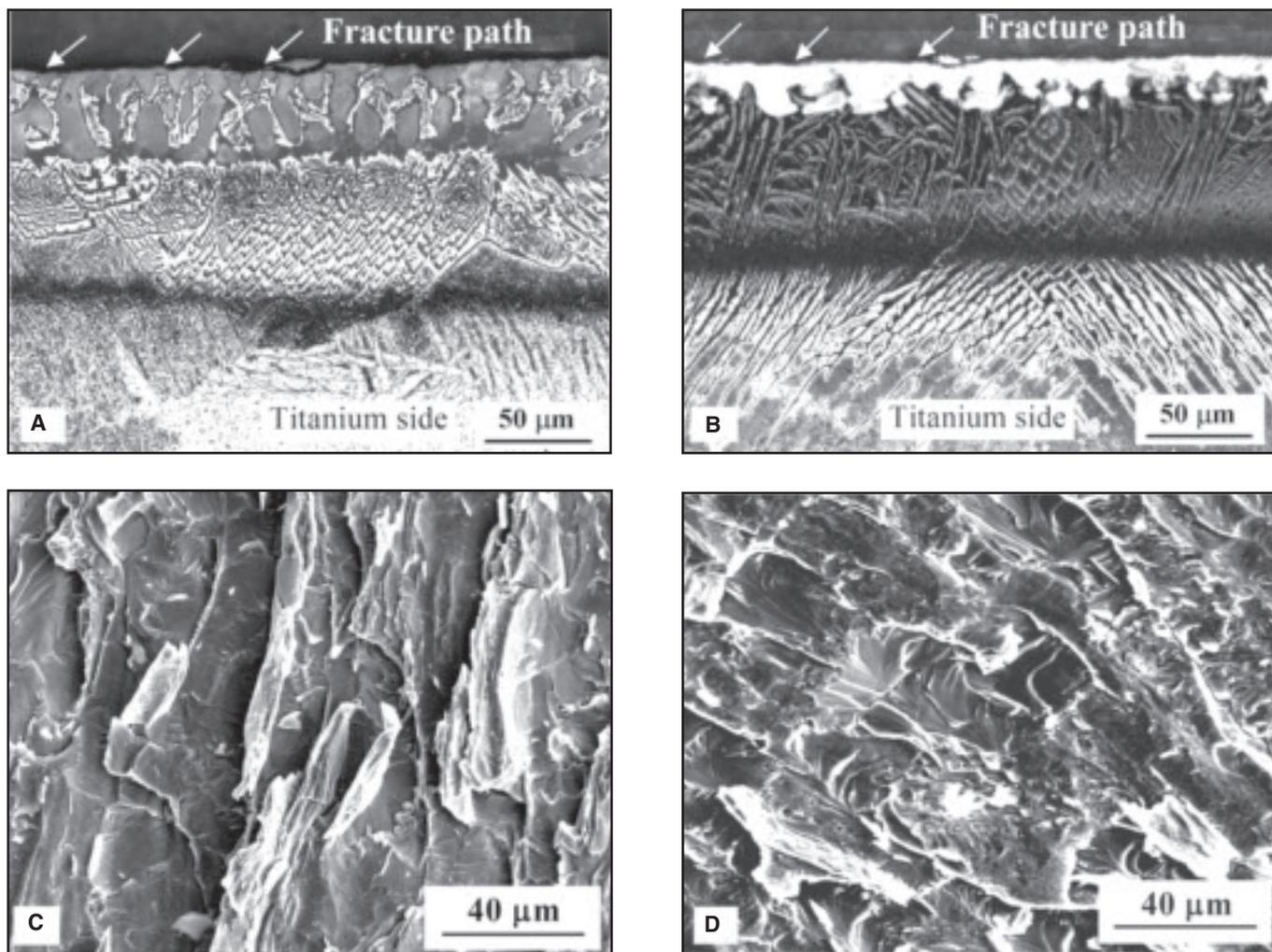


Fig. 8 — Cross-section fracture path and fracture morphology. A — Fracture path for a joint brazed at 1000°C (1832°F); B — fracture path for a joint brazed at 970°C (1778°F); C — fracture morphology for a joint brazed at 1000°C; D — fracture morphology for a joint brazed at 970°C.

the joint. However, the lower shear strength of the joint brazed at a temperature of 970°C (1778°F) could be attributed to the incomplete fusion at some points of the interfacial area, since the brazing temperature was not high enough to completely fuse the brazed alloy.

The fracture path after having performed the shear test is shown in Fig. 8A and B at brazing temperatures of 1000°C (1832°F) and 970°C (1778°F), respectively. As expected from the values of hardness measurements, in all joints the fracture path took place at the interfacial region between steel and the brazing alloy in between FeTi and Fe₂Ti phases. The fracture morphologies corresponding to previous fracture paths are presented in Fig. 8C and D. Massive cleavage fracture was highly prominent at both brazing temperatures.

X-ray diffracton was utilized in order to detect the phase constituent in the fracture surfaces after having performed the

shear test. X-ray diffraction patterns from fractured surfaces of the titanium side at brazing temperatures of 1000°C (1832°F) and 970°C (1778°F) were analyzed as shown in Fig. 9A and B. The test results indicate that the interface phase consisted of Ti, Cu, Fe, Mn, FeTi, Fe₂Ti, and Mn_xTi, where x is 1, 2, or 5. Therefore, XRD not only confirmed the presence of Fe₂Ti and FeTi intermetallics, but also suggested the presence of Mn_xTi at the fracture surface. The occurrence of Mn_xTi phases has not been observed in SEM micrograph, perhaps due to its low volume fraction.

Conclusions

The furnace vacuum brazing was carried out between commercially pure titanium and low-carbon steel using 100 μm (0.004 in.) copper-based brazing alloy. The brazing was carried out in the temperature range between 930° to 1000°C

(1706° to 1832°F) for 15 min. The characterization of the transition joints reveals the following:

1) Sound titanium/steel brazed joints were obtained with the copper-based brazing alloy at temperatures of 970°C (1778°F) and 1000°C (1832°F), while the temperature of 930°C (1706°F) was not high enough to completely melt the filler alloy.

2) Interaction layers containing α-β Ti, Fe₂Ti, FeTi, and TiC were formed at the interfacial area at brazing temperatures of 1000°C (1832°F) and 970°C (1778°F).

3) The average shear strength of the joint showed the highest values at the temperature of 1000°C (1832°F) compared to joints brazed at 970°C (1778°F) and 930°C (1706°F). In spite of the formation of thick FeTi intermetallic compound at a brazing temperature of 1000°C (1832°F), the bond strength improved due to the complete coalescence of the mating surfaces.

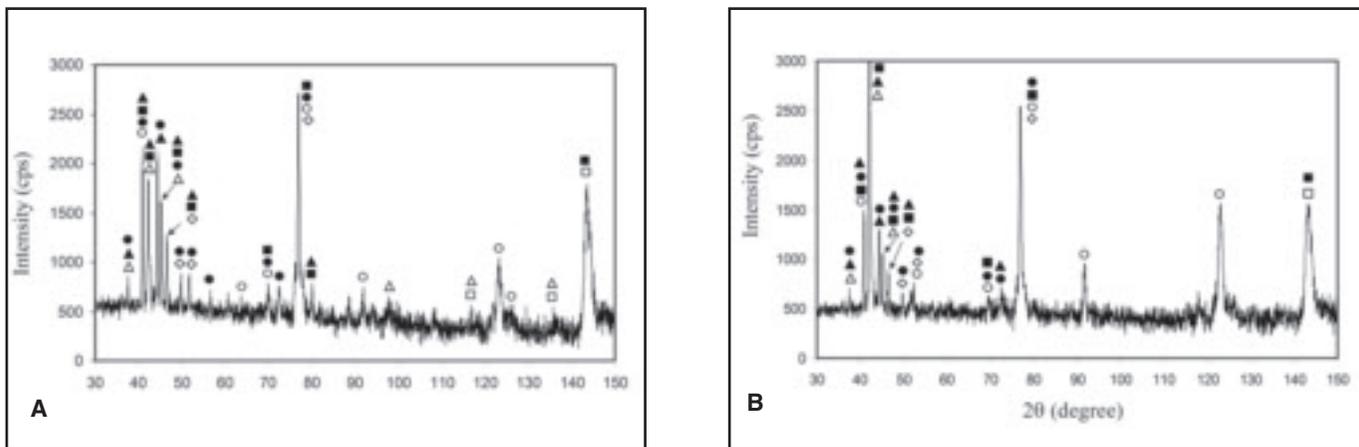


Fig. 9 — X-ray diffraction pattern of fracture surfaces of titanium side. A — Joint brazed at 1000°C (1832°F); B — joint brazed at 970°C (1778°F). Where diffraction lines from Ti, Fe, Cu, Mn, FeTi, Fe₂Ti, and Ti_xMn are indicated by ○, △, □, ◇, ■, ▲, and ●, respectively.

4) At all brazing temperatures, the fracture took place at the interfacial region between steel and the brazed alloy as a result of formation of intermetallic compounds of FeTi and Fe₂Ti.

5) XRD analyses not only confirmed the presence of Fe₂Ti and FeTi intermetallics, but also suggested the presence of manganese-rich titanium intermetallic at the fracture surface.

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