JMEPEG (2012) 21:696–700
DOI: 10.1007/s11665-012-0121-7 1059-9495/$19.00

Preliminary Investigation on Brazing Performance of Ti/Ti and Ti/Steel Joints Using Copper Film Deposited by PVD Technique

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(Submitted September 19, 2011; in revised form November 9, 2011)

Microstructural aspects and bonding characteristics of vacuum brazed Ti/Ti and Ti/steel were investigated. A thin-copper film, with different thicknesses, was deposited on the brazed metals by physical vapor deposition technique to serve as a brazing filler metal. Test joints were processed at a temperature of 910 °C and 15 min holding time. The resultant joints were characterized to determine the brittle intermetallic compound in the interfacial layer and the shear strength of the joints were tested. Our preliminary experimental results showed that sound joints with a good wetting quality, lack of pores and cracks can be achieved. Intermetallic phases such as Ti_2Cu, TiCu, FeTi, and Fe_2Ti were predicted from the chemical analyses. The Ti/Ti joints achieved a higher shear strength than the Ti/steel joints and there is a tendency for the tension shear strength to increase when a thick Cu-deposited layer is used.

Keywords brazing, joint microstructure, PVD, shear strength, steel, titanium

1. Introduction

With the increased use of light metals such as titanium alloys in various industrial sectors, joining titanium alloys to itself and titanium alloys to steel has become an increasingly important task. Unfortunately, the joining of titanium to steel alloys is not an easy task. The solubility of titanium in ferrite (α iron) reaches its maximum at 8.7 wt.% Ti at the eutectic temperature of 1289 °C, but decreases significantly at lower temperatures. Meanwhile, the limit of the austenite field is placed at 0.5 wt.% Ti (Ref 1). This limited solubility of titanium in iron makes joining titanium alloys to steels by conventional fusion welding processes very difficult.

Existing literature reveals that diffusion welding has been successfully used to join titanium to itself and to steel alloys. However, the great care required in the surface preparation stage and the impracticality of this method for mass production has limited the usage of this process (Ref 2-6). The difficulty to bond titanium with other metals could be solved using brazing techniques. Brazing is beneficial because it involves the melting of the filler material only, thus eliminating problems that occur when fusing dissimilar metals. Moreover, brazing enables to join many dissimilar metals without severe distortion, so that this process has been widely used for this kind of applications. It was reported that brazing foils such as pure silver, silver-based alloys, titanium-based alloys, aluminum-based alloys, and copper-based alloys were utilized to braze titanium to dissimilar metals (Ref 7-12). The possibility of using new coating technologies in brazing such as PVD opens many new avenues for difficult-to-join materials. The PVD technique can apply specified metal elements of a small dosage on substrate metals to serve as brazing filler and create simple and effective joints (Ref 13). Because of the little amount of filler metal, a very thin liquid phase forms by a transient liquid phase process which enables brazing at low temperatures. Therefore, the objective of this investigation is to demonstrate the brazing feasibility of commercially pure titanium to itself and to low carbon steel with a deposited copper film. The focus is hereby on the interfacial microstructure and strengths of the joints.

2. Experimental Procedure

2.1 Materials

The experimental materials used are commercially pure titanium (CPTi) grade 2 and low carbon steel AISI 1008 which was obtained in the form of sheets of 2 mm thickness. The titanium and steel were cut into 30 × 25 mm chips for shear strength testing and 12 × 10 mm chips for a microstructure analysis. A smooth surface is necessary for the following Arc-PVD process to provide an even thickness of the coatings. Thus, the bond surfaces were prepared using different grades of grinding papers followed by polishing up to 1 μm before PVD coating.

This article is an invited submission to JMEP selected from presentations at the Symposia "Wetting, soldering and brazing" and "Diffusion bonding and characterization" belonging to the Topic "Joining" at the European Congress and Exhibition on Advanced Materials and Processes (EUROMAT 2011), held September 12-15, 2011, in Montpellier, France, and has been expanded from the original presentation.

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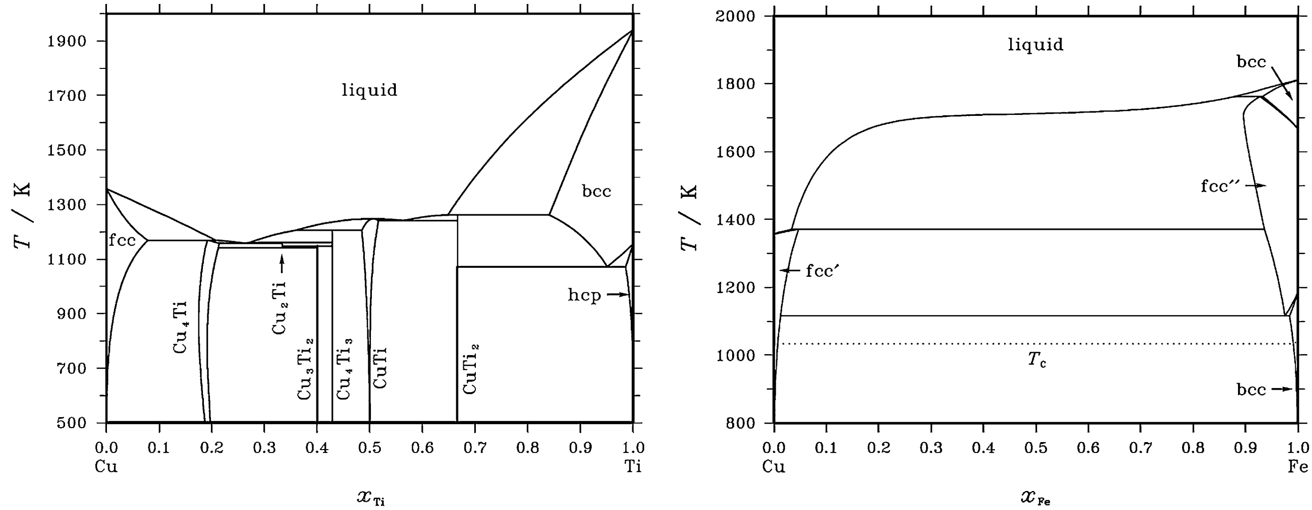


Fig. 1 Cu-Ti and Cu-Fe phase diagrams

2.2 Arc-PVD-Deposited Filler Metals

Selecting material for the PVD cathodes is of fundamental importance. The selected material has to be metallurgically compatible with the base metal which implies that the base metals and brazed metal can be combined without the production of deleterious constituents or phases. Additionally, the selected material has to form low melting alloys (eutectic or near eutectic) with the base metal as well. An example of this phenomenon is presented in the Ti-Cu and Fe-Cu binary phase diagram (Fig. 1). Alloying copper into the titanium matrix lowers the melting temperature of titanium until a eutectic composition is formed at 960 °C. At the eutectic temperature, titanium alloy transfers directly into eutectic structure composed of Ti_2Cu + TiCu. On the other hand, copper does not form brittle intermetallic compounds (IMCs), neither with iron nor with carbon. Moreover, it is a soft metal which deforms and accommodates the stresses caused by mismatch in thermal expansion coefficients. Additionally, copper has also a low prize compared to other soft metals which could be employed with similar results (Ag, Au, or Pt). Therefore, copper was chosen as the deposited filler metal for the intended combinations of metals.

Before the actual coating process was started the surface of the samples was plasma-etched. Energized target ions were accelerated onto the surface of the substrate due to a high bias voltage and removed impurities at the surface. Besides the cleaning effect, an activation of the surface takes place that increases the adherence between the substrate and the layer (Ref 14). The employed coating parameters are listed in Table 1. The coating parameters were adjusted to deposit copper layers of different thicknesses.

2.3 Brazing Condition

The pre-coated specimens were kept in contact using a stainless steel fixture at an overlap width equal to 6 mm and were then carefully placed into a vacuum furnace. Initially, the samples were heated up to a temperature of 50 K, below the specified brazing temperature, for a holding time of 5 min. This step aimed at achieving the thermal equilibrium of the couple. The sample was then heated up to brazing temperature and kept at this temperature for 15 min before it slowly cooled down to room temperature.

Table 1 The parameters used for the coating process

Etching	
Voltage, V	−1000
Max. temperature, °C	300
Coating	
Deposition rate, AH	45, 90, 135
Bias-voltage, V	−36
Max. temperature, °C	350
Average thickness of coating layer, μm	6, 10, 15

2.4 Microstructure Observation and Mechanical Testing

The polished microstructures of the joints were examined with a light optical microscope and a scanning electron microscope (SEM), equipped with an energy dispersive x-ray (EDX) for chemical analysis. Tensile shear specimens were machined from brazed lap joints as suggested by Harvey et al. (Ref 15). The test was carried out at room temperature at a displacement rate of 0.5 mm/s. Three samples were used to calculate the average shear strength of the joint.

3. Results and Discussion

3.1 Microstructure and Phase Analysis

The cross sections of the titanium and steel samples after PVD coating are shown in Fig. 2. A layer of copper is continuously formed at both substrates. The thickness of deposited layer is inhomogeneous due to the applied arc-PVD process. Typically, droplets which are responsible for the irregularities at the surface form during the coating process. The thickness of the layer was increased by increasing the deposition rate. This development initiated at almost 6 μm at 45 AH till 15 μm at 135 AH.

The microstructure of the titanium/titanium joint is shown in Fig. 3(a). At low copper thickness (Fig. 3a), a defect joint is obtained since a close contact between the two parts of the joint was not achieved. It is suggested that the thickness of the copper layer was not sufficient enough to accommodate the stresses rising from the thermal expansion coefficients mismatching between the filler metal and the base metal. This defect did not appear when using deposited copper layers with a greater thickness, as shown in Fig. 3(b) and (c). It is clear that a sound joint was obtained since a homogeneous microstructure without voids or cracks was observed along the joint. The stress is decreased with the increase of the filler metal thickness. In the case of a very small brazing gap, the deformation gradient in the filler is much larger, which brings more difficulties in stress relief and causes an increase of the residual stress (Ref 16).

A clear view of the microstructure, formed at the interfacial area, and the EDX analyses are shown in Fig. 4. The diffusion of Cu (strong β-stabilizing elements) in the titanium substrate lowers the eutectoid transformation temperature of Ti and an α-β Ti regions, almost 60 μm thick, form due to the decomposition of β-Ti during cooling (Ref 17). The α-β Ti regions are clearly shown in area *A*, which contains a high percentage of copper. According to the Ti-Cu binary phase diagram, β-Ti dissolves 13.5 at.% Cu at 1005 °C, meanwhile α-Ti dissolves up to 1.6 at.% Cu at 790 °C (Ref 18). It can be seen that the interfacial structure of the joint consists of two interaction layers marked as B zone next to the base metal and the interior of the braze marked as C zone. The average width of the B zone is 2 μm, while the width of interior braze is recorded 12 μm.

The microstructure of the titanium/steel is shown in Fig. 5. Sound joints were achieved using different deposition rates. It is observed that the brazed areas are narrower than their comparable area in case of titanium/titanium joints owing to the limited mutual solubility of copper in steel. On the other hand and similar to the titanium/titanium joint, a remarkable amount of diffusion occurred between the copper deposited layer and the titanium substrate, which resulted in the formation of α-β Ti regions with similar thickness to the previous case.

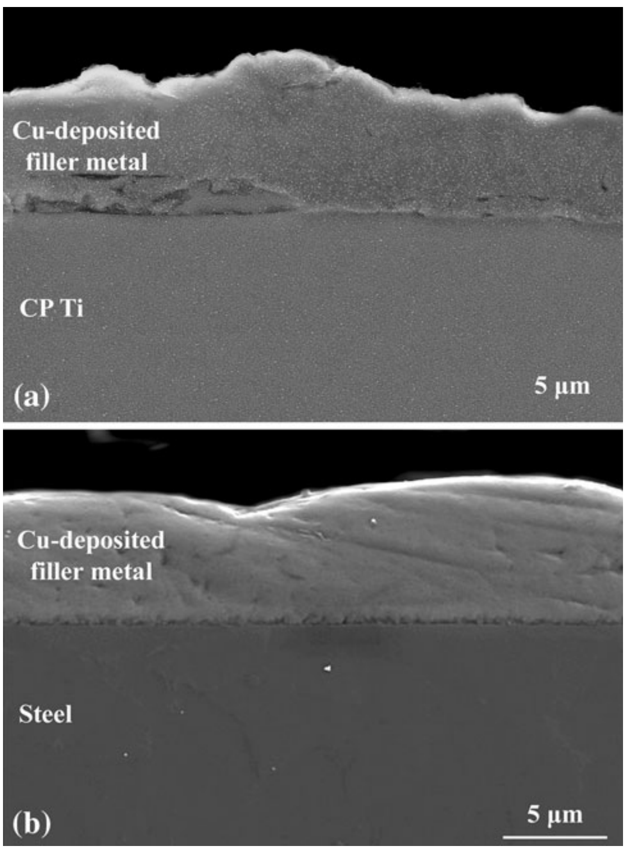
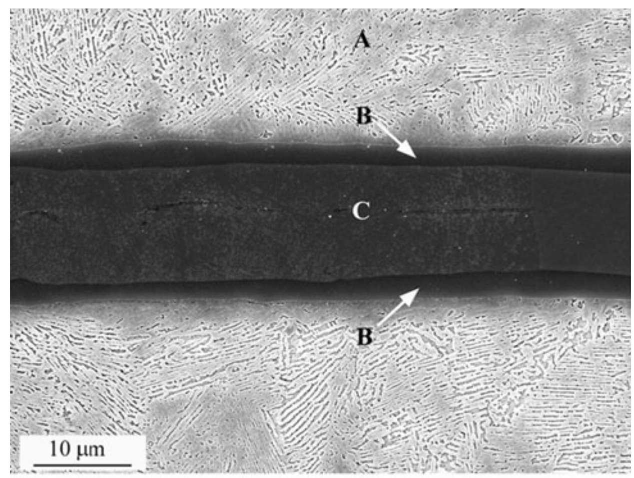


Fig. 2 Cu-PVD deposited on titanium and steel substrates; deposition rate is 45 AH



Symbol	Chemical compositions, at. %		
	Ti	Cu	Suggested phase
A	93.17	6.83	α-β Ti
B	66.55	33.45	Ti2Cu
C	50.97	49.03	TiCu

Fig. 4 SEM microstructures of the titanium/titanium joint; deposition rate is 135 AH and holding time is 15 min

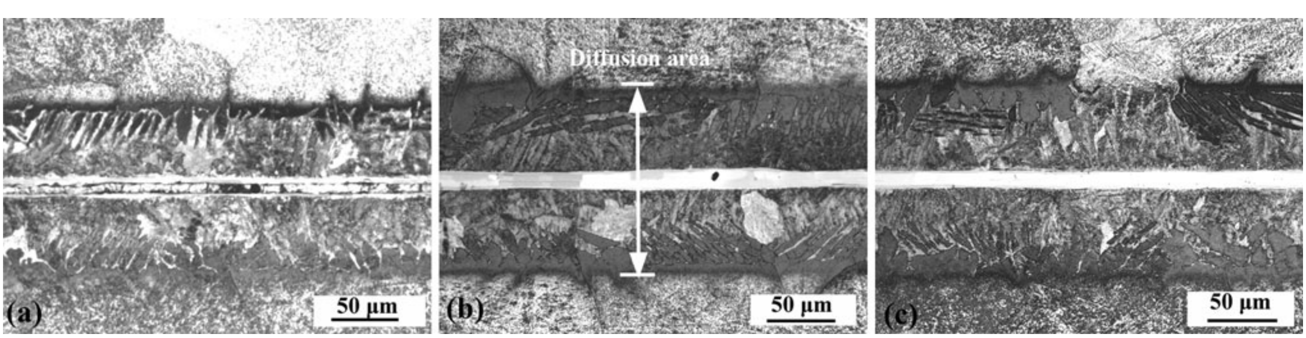


Fig. 3 Microstructure of the brazed titanium/titanium joint at different copper-coated layers; (a) 45 AH, (b) 90 AH, and (c) 135 AH

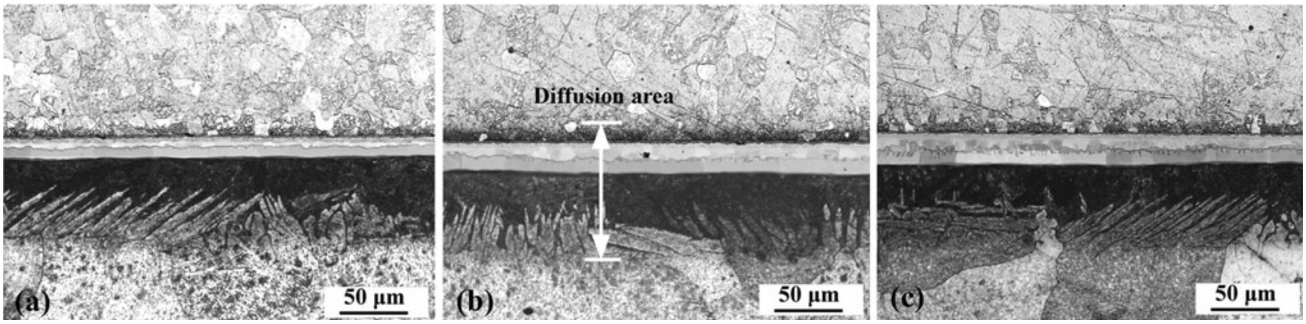
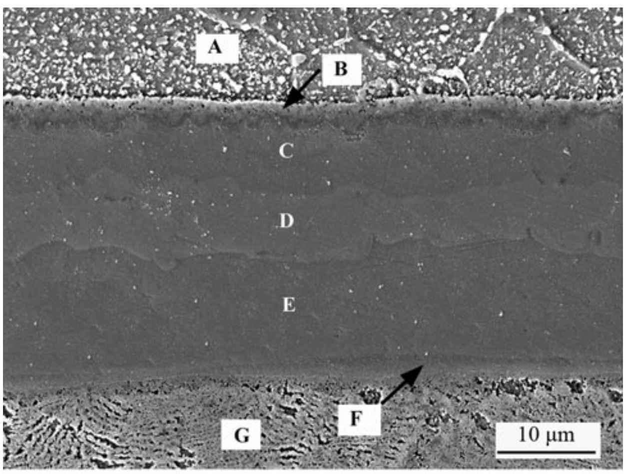


Fig. 5 Microstructure of the brazed titanium/steel joint at different copper-coated layers; (a) 45 AH, (b) 90 AH, and (c) 135 AH



Symbol	Chemical compositions, at. %			
	Ti	Cu	Fe	Suggested phase
A	3.10	1.08	95.82	α Fe
B	33.76	1.08	65.16	Fe_2Ti
C	50.57	15.90	33.53	TiFe + Cu
D	41.81	48.77	9.42	T2, $Ti_{0.4}Fe_xCu_{0.6-x}$
E	48.54	50.88	0.58	TiCu
F	67.12	32.56	0.32	Ti_2Cu
G	92.44	7.33	0.23	α-β Ti

Fig. 6 SEM microstructures of the titanium/steel joint; deposition rate is 135 AH and holding time is 15 min

Figure 6 shows the SEM microstructure of the joint, brazed at a deposition rate of 135 AH together with an EDX analyses at different areas. The titanium showed a high diffusion rate in the brazed area up to the level that it even reached to the steel side with a quite high concentration (see area *A*). The steel/copper interface showed presence of Fe_2Ti; meanwhile, the titanium/copper interface was enriched by Ti_2Cu. The atomic percentages of elements together with the ternary Ti-Fe-Cu diagram suggests the presence of TiCu, T2 ($Ti_{0.4}Fe_xCu_{0.6-x}$), TiCu + Fe phases in the interior of the brazed area (Ref 19).

3.2 Mechanical Properties of Joints

The fracture tensile shear strength was calculated as the failure load divided by the overlap area. The scattering of the shear test results were within 7%. The average shear strength of the joint was higher in case of the titanium/titanium joint than with dissimilar joints. The dissimilar joint achieved maximum shear strength of 44 MPa. Meanwhile, the similar joints achieved maximum shear strength of 62 MPa. Titanium/steel joints might be weaker because of the accumulation of residual stresses during brazing owing to the difference in thermal expansion coefficient between steel and titanium. Additionally, the phase analyses at the dissimilar joint were more complicated and contained the most harmful Fe-Ti IMCs as well. Figure 7 shows the average tensile shear strength of all the combinations. Fracture of joints took place mainly at Ti_2Cu phase in case of Ti/steel joints. Meanwhile, Ti/Ti joints showed always fracture path at TiCu phase. The effect of the thickness of the copper-deposited layer was not completely clarified. However, it is shown that there was a small tendency to improve the tensile shear strength at the highest deposition rate in both types of joints.

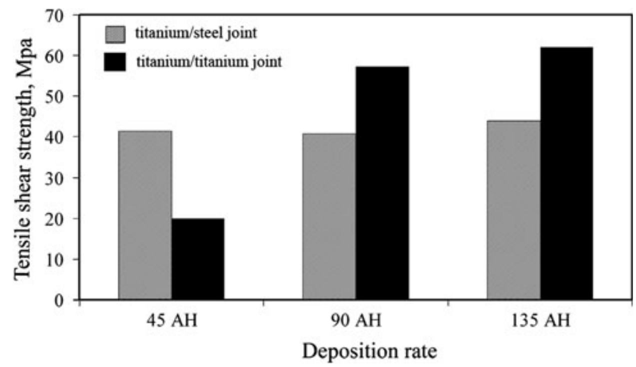


Fig. 7 Tensile shear strength of the brazed joints

A more detailed study to investigate the effect of varying brazing temperatures and holding times at the brazing temperatures are planned for the future. The correlation between the microstructure, filler metal deposition thickness, brazing parameters, and the resultant mechanical properties will be clearly explored in this study.

4. Conclusions

A thin copper-PVD-coating layer was employed successfully as a brazing filler metal for titanium/titanium and titanium/steel joints. The interfacial structure, microstructural evolution, and the joint strength were experimentally assessed. It was shown that the deposited filler metal clearly reacted with the titanium substrate, resulting in the formation of an α-β Ti regions and Ti-Cu IMCs. Additionally, Fe-Ti IMCs were formed at the steel substrate. The evaluating of the shear strength of the joints showed that the shear strength of the joint was higher in case of the titanium/titanium joint than the dissimilar joints. The dissimilar joint achieved average shear strength of 44 MPa. Meanwhile, the similar joints achieved average shear strength of 62 MPa.

Acknowledgment

The author gratefully acknowledges the financial support from the German Research Foundation (DFG) with project No. TI343/31-1.

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