

Brazing of titanium to steel with different filler metals: analysis and comparison

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Abstract Evaluations of vacuum brazed commercially pure titanium and low-carbon steel joints using one copper-based alloy (Cu–12Mn–2Ni) and two silver-based braze alloys (Ag–34Cu–2Ti, Ag–27.25Cu–12.5In–1.25Ti) have been studied. Both the interfacial microstructures and mechanical properties of brazed joints were investigated to evaluate the joint quality. The optical and scanning electron microscopic results showed that all the filler metals interact metallurgically with steel and titanium, forming different kinds of intermetallic compounds (IMC) such as CuTi, Cu₂Ti, Cu₄Ti₃, and FeTi. The presence of IMC (interfacial reaction layers) at the interfacial regions strongly affects the shear strength of the joints. Furthermore, it was found that the shear strength of brazed joints and the fracture path strongly depend on the thickness of the IMC. The maximum shear strength of the joints was 113 MPa for the specimen brazed at 750 °C using an Ag–27.25Cu–12.5In–1.25Ti filler alloy.

Introduction

Titanium and its alloys show an excellent corrosion resistance and high-strength-to-weight ratios, which make them ideal candidates especially for the use in two areas of application: corrosion resistant service and specific strength efficient structures. Normally, low strength, unalloyed, commercially pure titanium (CP Ti) is used in the fabrication of tanks, heat exchangers, reactor vessels,

desalination processes, and power generation plants [1–3]. The major disadvantages of this metal are high cost and difficulty in bonding with other materials. Among methods of its cost reduction is the joining of titanium to steel.

The conventional fusion welding techniques between Ti and stainless steel have resulted in the segregation of chemical species, stress concentration, and the formation of thick intermetallic compounds (IMC). Especially the combination between Ti and Fe alloys generate many of IMC at the interface because Ti and Fe are not completely soluble in solid state [4, 5]. Fusion welding methods also involve melting and solidification of the base metals, which results in a distortion of the shape of the welded metals and an excessive generation of strain at the interface due to the difference in the coefficient of linear expansion when joining of dissimilar metals.

Existing literature reveals that diffusion welding has been used successfully to join titanium 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 [6–8]. The difficulty of bonded titanium with other metals could be relieved by 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 these applications.

It has been reported that pure silver, silver-based alloys, titanium-based alloys, and copper-based alloys were used to braze titanium to steel [9–12]. The melting point of pure silver is 961 °C and can be greatly decreased by alloying copper into the silver matrix. Therefore, the Ag–Cu eutectic braze alloy was selected as a filler metal for vacuum brazing of titanium to steel. Active brazing alloys

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were taken because of their better wettability when compared to inactive filler metals. Chemical composition modifications of the silver–copper eutectic braze filler showed a positive result in the strength of the joint by alloying the filler with indium and titanium [13]. Since a lower brazing temperature is preferred for most brazing processes, Ag–27.25Cu–12.5In–1.25Ti was selected because of its low solidus 605 °C and liquidus 715 °C temperatures. Moreover, Cu–12Mn–2Ni was chosen as a brazed filler metal because it provides good chemical compatibility in fusion reaction applications and has a good wettability to many materials. It is suggested also that the high percentage of Mn further improves the wettability.

Detailed investigation of titanium to steel joints using different filler metals were separately performed by the authors. Optimal brazing temperatures, the temperatures at which the best microstructure and mechanical properties were achieved, have been reached in the joints for each filler metal used [14–17]. The objective of this investigation is focused on brazing of CP Ti to low-carbon steel using two silver-based alloys and one copper-based alloy at their optimal brazing temperatures, which were determined in our previous studies, and to compare the results in order to predict the main controlling factors, which govern the quality of the joints. Microstructures as well as mechanical properties are the main focus of the study.

Experimental procedures

Materials

CP Ti and low-carbon steel were received in the form of plates of 2 mm thickness. The chemical composition of the material, in wt%, as indicated in the supplier’s test certificate was 0.08% C, 0.20% Fe, 0.03% N, 0.18% O, 0.02% H, and balance Ti. On the other hand, the composition of steel, in wt%, was 0.12% C, 0.05% P, 0.05% S, 0.05% Mn, and balance Fe. Specimens were cut into 125 mm × 28 mm × 2 mm strips for shear strength testing and 10 mm × 10 mm × 2 mm strips for microstructure analysis. Prior to brazing, one face of each specimen was processed in order to achieve a predetermined degree of

roughness using 1200 mesh grinding paper. The samples were then degreased in an ultrasonic bath using acetone.

The brazing was carried out using two silver-based alloys and one copper-based alloy. Table 1 shows the composition, solidus/liquidus temperatures, dwell time, and the optimal brazing temperatures, which have been previously reached. The brazing foils, 100-µm thick, were cleaned in acetone before brazing and then sandwiched between the overlapped areas of the parent metals.

Brazing procedure

The width of the titanium to steel overlap was kept at 6 mm since it is recommended to use a lap width of not more than thrice the thickness of the base metals to achieve high strength for the joint [16]. The joints were fixed with stainless steel clamp, and then carefully placed into a vacuum furnace. Initially, the samples were heated up to a temperature of 50 K below the solidus temperature of the filler alloy for a dwell time of 5 min. This step is to achieve the thermal equilibrium of the couple. The sample was then heated up to the brazing temperature, as it is shown in Table 1. All the specimens were furnace-cooled to room temperature.

After bonding, the brazed samples were cut, mounted in epoxy, polished, and then etched by 5% HF, 20% HNO₃, and 75% glycerol for 60 s for the titanium side and 3% Nital solution for the steel side. The microstructures were examined using optical and scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDS). A hardness measurement was performed with the help of a Vickers hardness testing machine with 25 s impressing time. Tensile shear specimens were machined out from brazed lap joints in accordance to AWS C3.1-63 (Standard Test for Brazed Joints). The test was carried out at room temperature and with displacement rate of 0.5 mm/s. Three samples were used to calculate the average shear strength of the joint.

Results

Vacuum brazing of Ti/Cu–12Mn–2Ni/steel joint

Microstructure examination of the interface reveals that several interaction layers occur between the copper-based

Table 1 Brazing filler investigated

Base	Composition (wt%)						Solidus (°C)	Liquidus (°C)	Actual brazing temperature (°C)	Dwell time (min)
	Ag	Cu	Ti	In	Mn	Ni				
Silver	Bal.	34	2	–	–	–	780	810	850	15
Silver	Bal.	27.25	1.25	12.5	–	–	605	715	750	15
Copper	–	Bal.	–	–	12	2	970	990	1000	15

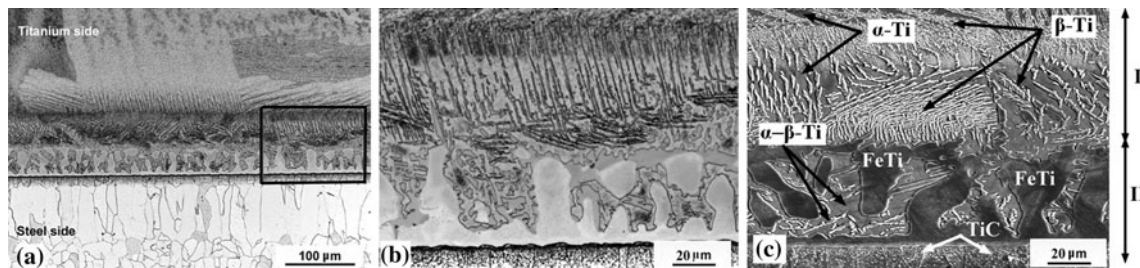


Fig. 1 **a** Microstructure features of the titanium/steel brazed joint at 1000 °C for 15 min using Cu–12Mn–2Ni filler metal, **b** enlarged view at the interface, **c** SEM microstructure at the interface

brazing alloy and the substrates. Figure 1a displays microstructure features of the titanium/steel joint brazed at temperatures of 1000 °C for 15 min. The steel–copper bonding interface is planar in nature and a thin diffusion layer was revealed in contrast to the titanium–copper interface, which is characterized by the presence of different interaction layers.

Figure 1b and c shows a close up view of the interfacial microstructure by optical microscope and SEM, respectively. The interfacial region can be divided into two characteristic zones. Zone I is the α - β -Ti region since 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 [12, 18]. The β -Ti takes the form of bright needles, whereas the α -Ti has a dark plate-like structure between the needles of β -Ti (see Fig. 1c). The α - β -Ti phase also formed close to the steel/copper-based interface but with a higher content of Fe and Cu. Table 2 shows the chemical compositions of the marked phases in Fig. 1c.

Zone II, in Fig. 1c, is considered to be the intermetallic region and consists of three main IMC. Most of this zone is consumed by FeTi + Cu intermetallic phase (FeTi). According to Van Beek et al. [19], the Fe–Ti–Cu ternary alloy phase diagram suggests that nearly 38 at.% Cu could be dissolved in FeTi. On the other hand, close to the FeTi phase at the steel side, a scattered black phase was detected in the ferrite matrix. It is suggested on the basis of its chemical analysis that this phase is a TiC phase, although the carbon content was not precisely measured. The

formation of this region provides evidence for the high diffusion of Ti. It is worth noting that the average thickness of zone II is almost 20 μ m which might deteriorate the shear strength of the joints. The intermetallic region is located in this case at the steel/copper-based interfacial region in contrast to its location when using Ag–34Cu–2Ti filler alloy.

Figure 2 shows microhardness measurements of the interfacial microstructure. IMC presented the highest hardness values in spite of its location at the steel/copper-based interfacial region. The average shear strength observed for the joint was 61 MPa and the fracture path follows logically the interaction layers at the steel/copper-braze alloy. The fracture morphology corresponding to the previous fracture path showed massive cleavage fractures owing to the presence of thick IMC at the fracture surface. Chemical analysis of the fracture surface showed that it is

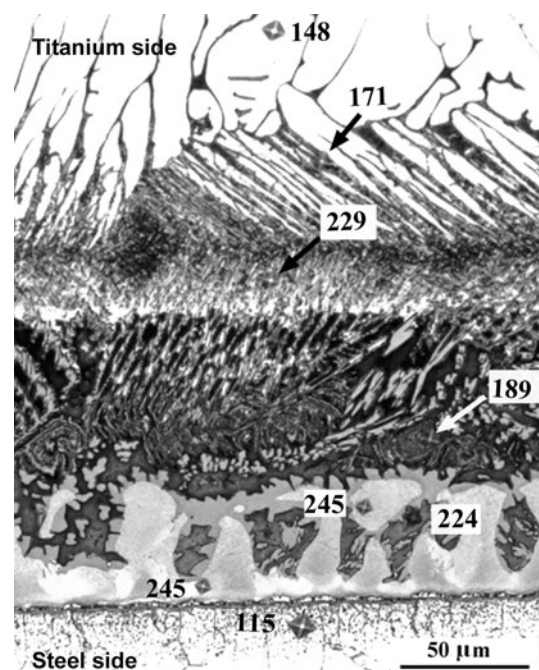
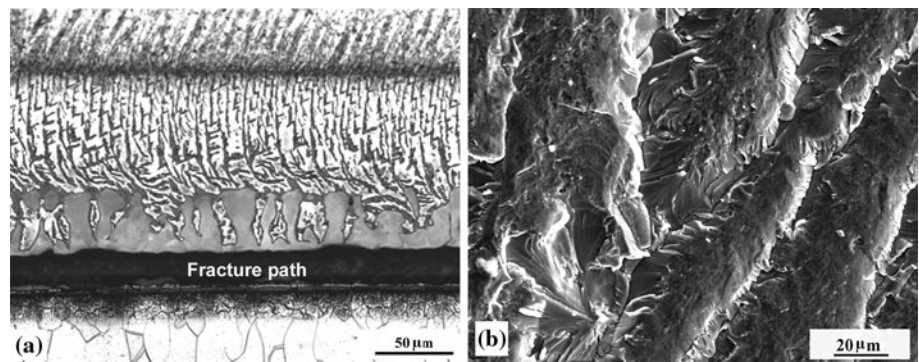


Fig. 2 Microhardness measurements of the titanium/steel joint brazed at 1000 °C for 15 min using Cu–12Mn–2Ni filler metal

Table 2 Average chemical analyses at areas shown in Fig. 1c

Suggested phase	Chemical analyses (at.%)				
	Ti	Cu	Fe	Mn	Ni
α -Ti	85.54	9.78	0.88	1.89	1.91
β -Ti	99.21	–	0.22	0.57	–
α - β -Ti	74.11	15.83	5.31	2.10	2.65
FeTi	48.44	22.76	26.8	1.12	0.88

Fig. 3 Cross section of fracture surface (a) and fracture morphology (b) of the titanium/steel joint brazed at 1000 °C for 15 min using Cu–12Mn–2Ni filler metal



highly consistent with the FeTi intermetallic phase. Figure 3 shows the fracture path and fracture morphology for this joint.

Vacuum brazing of Ti/Ag–34Cu–2Ti/steel joint

Microstructure examination of the interface reveals the formation of reaction layers close to the titanium side in contrast to the steel side, which showed no reaction layer with the silver-based braze alloy. A coarse grain structure was formed at the steel boundary to the silver–brazed alloy. This structure results from diffusion growth accompanied by recrystallization of the steel substrate at high temperature. Figure 4a displays microstructure features of the titanium/steel joint brazed at a temperature of 850 °C for 15 min.

Figure 4b and c shows close up views of the microstructure at the titanium/silver-based alloy by optical microscope and SEM, respectively. The interfacial region can be divided into three characteristic zones. Zone I is the titanium parent metal without evidence of diffusion by elements of the brazed alloy since the EDS result of this zone was consistent with the base metal CP Ti. Table 3 shows the chemical compositions of the marked areas in Fig. 4c.

Zone II is considered to be the interaction and diffusion zone since a high amount of Ti was diffused from the titanium side to the brazed area close to the titanium substrate. It is clear that zone II is composed of at least three

Table 3 Average chemical analyses at areas shown in Fig. 4c

Suggested phase	Chemical analyses (at.%)		
	Ti	Cu	Ag
Ti ₂ Cu	68.44	29.06	2.5
TiCu	47.16	51.62	1.22
Cu ₂ Ti	28.52	69.23	2.25
Ag	2.38	12.34	85.28
Eutectic Ag–Cu	2.66	34.77	62.57

kinds of continuous reaction layers. The interpretation of the EDS reveals that intermetallic layers containing principally Ti and Cu were formed. Based on the Cu–Ti binary alloy phase diagram [20], the relative atomic proportion of these elements lies near the Ti₂Cu, TiCu, and Cu₂Ti stoichiometry, with additional traces of Ag. These phases are clearly visible in Fig. 4c. The measured average thickness of zone II is about 11.2 μm.

Zone III is considered to be the rest of filler alloy which has not interacted directly with the parent metals. This zone consists of three phases. The eutectic Ag–Cu phase, silver rich solid solution phase which formed duo to the consumption of Cu by Cu–Ti phases in the main alloy, and some scattered Cu₂Ti phase. These phases are also marked in Fig. 4c. These results are in agreement with those of previous research work [21, 22].

Figure 5 shows microhardness measurements of the interfacial microstructure. Similar to the joint brazed with a

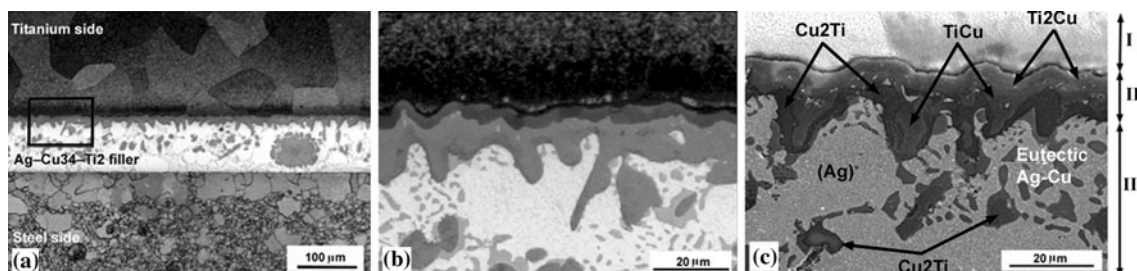


Fig. 4 a Microstructure features of the titanium/steel brazed joint at 850 °C for 15 min using Ag–34Cu–2Ti filler metal, b enlarged view at the titanium/filler metal interface, c SEM microstructure at the titanium/filler metal interface

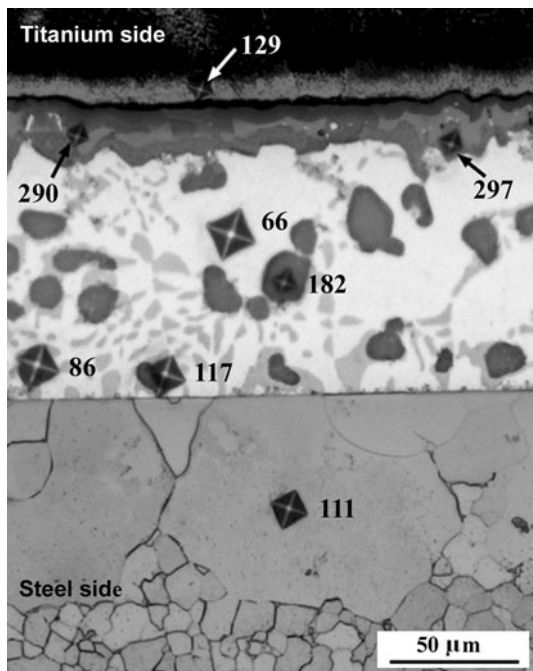
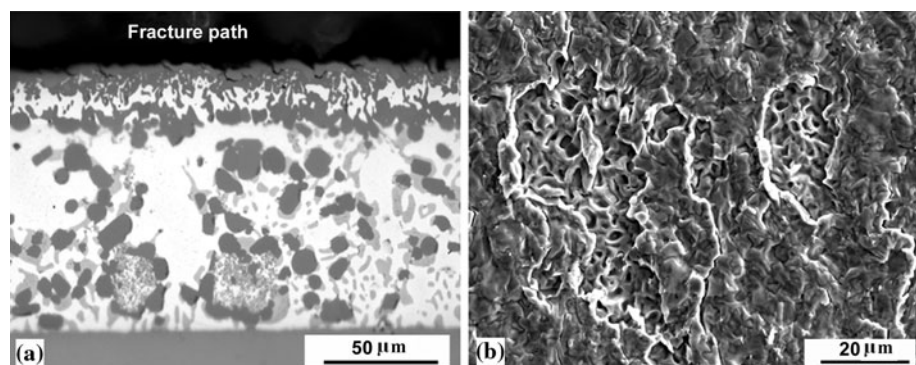


Fig. 5 Microhardness measurements of the titanium/steel joint brazed at 850 °C for 15 min using Ag–34Cu–2Ti filler metal

copper-based Cu–12Mn–2Ni filler alloy, the interaction and diffusion area, zone II, which contains mainly intermetallic phases, presented the highest hardness values. This zone is considered sensitive to initiation of cracks during loading in the shear test. The structure in zone III is softer than zone II, this can help to reduce some stress. The average shear strength observed for the joint was 63 MPa and the fracture path followed interaction layers at the titanium/silver–brazed alloy since it contains the most harmed structure in the joint. The fracture morphology corresponding to the previous fracture path showed cleavage fracture. The brittle nature of this fracture is most likely due to the presence of Ti–Cu-rich phases in the brazed joint. Figure 6 shows the fracture path and fracture morphology for this joint.

Fig. 6 Cross section of fracture surface (a) and fracture morphology (b) of the titanium/steel joint brazed at 850 °C for 15 min using Ag–34Cu–2Ti filler metal



Vacuum brazing of Ti/Ag–27.25Cu–12.5In–1.25Ti/steel joint

A representative cross-sectional microstructure of the brazed joints at brazing temperatures of 750 °C is shown in Fig. 7a. The brazed area has a fine structured feature compared to the previous joints. The entire microstructure of the brazed area consists of a matrix of Ag solid solution (Ag) alloyed with Cu and In. The ternary Ag–Cu–In phase diagram indicates the presence of this phase under equilibrium condition [23]. Additionally, a mixed structure containing copper solid solution phase (Cu) and Cu₄Ti was formed in the Ag matrix. Tiny precipitates are randomly distributed in the Ag solid solution matrix. This phase is too fine to be accurately analyzed by EDS. However, its chemical analysis suggested that it could be Ti₃In since the incorporation of titanium in braze metal increases at high temperatures and the solubility of In in Ti is quite high at high temperatures and decreases at lower temperatures according to the Ti–In binary phase diagram [24]. The interface microstructure can be divided into two characteristic zones, representing the continuous reaction layers at the titanium/silver-based alloy and steel/silver-based alloy. Figure 7b shows an SEM image of a titanium/silver-based alloy. The interfacial microstructure revealed the presence of three phases based on the chemical analysis. A thin α - β -Ti phase was formed close to titanium side in addition to Cu₄Ti₃ and Cu₂Ti phases which formed at the interface.

The interfacial microstructure at the steel/silver-based alloy revealed the presence of two phases as it is shown in Fig. 7c. The diffusion of copper into the steel substrate produces a solid solution with limited solubility [18]. It is assumed that eutectoid transformation $\gamma \rightarrow \alpha\text{Fe} + (\text{Cu})$ took place with a high content of αFe with respect to (Cu). Besides, a very thin interaction layer of FeTi + Cu intermetallic phase, previously mentioned in section “[Vacuum brazing of Ti/Cu–12Mn–2Ni/steel joint](#),” was formed close to the eutectoid layer. Table 4 shows the chemical compositions of the marked zones in Fig. 7b and c.

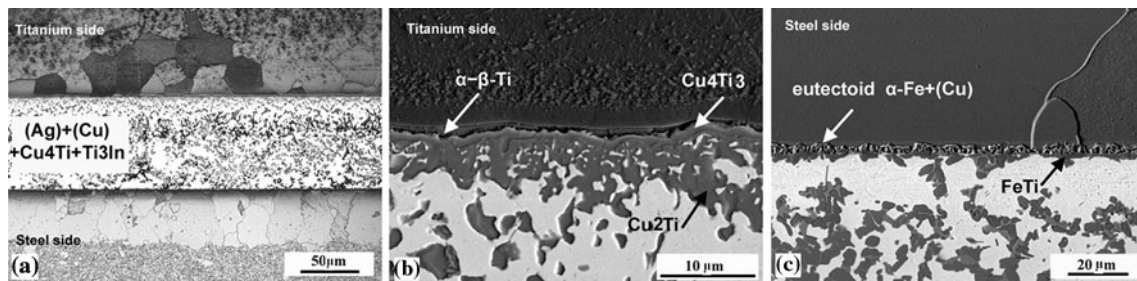


Fig. 7 a Microstructure features of the titanium/steel brazed joint at 750 °C for 15 min using Ag–27.25Cu–12.5In–1.25Ti filler metal, b SEM microstructure at the titanium/filler metal interface, c SEM microstructure at the steel/filler metal interface

Table 4 Average chemical analyses at areas shown in Fig. 7b and c

Suggested phase	Chemical analyses (at.%)				
	Ag	Ti	Cu	In	Fe
α - β -Ti	5.48	77.24	13.08	4.20	–
Cu ₄ Ti ₃	2.77	40.50	56.43	0.30	–
Cu ₂ Ti	1.38	32.61	65.72	0.29	–
α -Fe + (Cu)	1.86	1.47	2.67	–	93.73
FeTi	5.21	26.24	25.11	3.71	39.73

It was revealed that despite the formation of IMC at both sides of the joint, the average thickness reported is 6 mm at the titanium/silver-based alloy and 3 mm at the steel silver-based alloy, which is much lower than with the joints brazed with Ag–34Cu–2Ti and Cu–12Mn–2Ni filler metals.

Intermetallic layers at the interfacial regions still presented the peak hardness level compared to the rest of the structures in the joint as clearly shown in Fig. 8. The average shear strength observed for the joint was 113 MPa. The joints failed mainly at the interior of the braze, at the silver solid solution phase in contrast to the joints brazed with Ag–34Cu–2Ti and Cu–12Mn–2Ni filler metals. The fracture morphology, corresponding to the previous fracture path, showed a mixed dimple-cleavage structure with tearing regions, which is favorable for the strength of the joint. Figure 9 shows the fracture path and fracture morphology for this joint.

Discussion

Based on the previous study, CP Ti and low-carbon steel are successfully brazed using all employed filler metals. The CP Ti substrate readily reacts with the molten braze and forms reaction layers. α - β -Ti and Ti–Cu intermetallic are the main phases formed at the titanium/filler metals interfacial region. Meanwhile, the FeTi intermetallic phase is probably the phase formed at the steel/filler metals interfacial region. Regardless of the type of IMC formed at

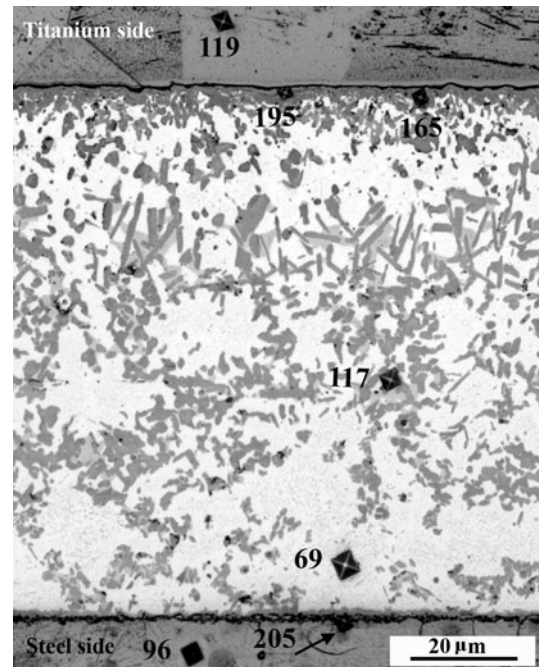
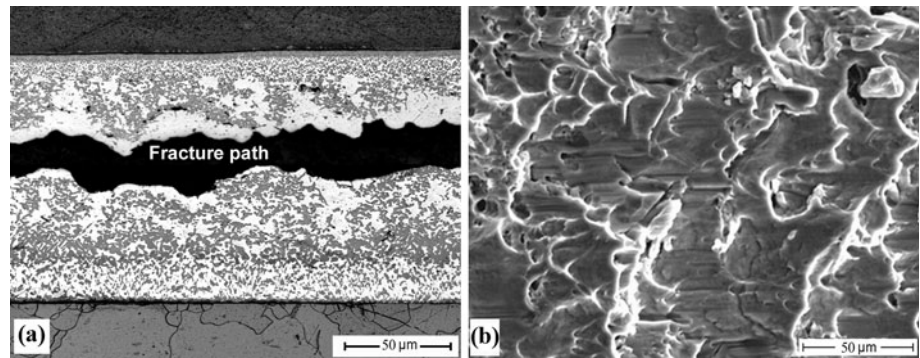


Fig. 8 Microhardness measurements of the titanium/steel joint brazed at 750 °C for 15 min using Ag–27.25Cu–12.5In–1.25Ti filler metal

interfacial regions, the presence of a thick layer of IMC is generally considered to be detrimental to the mechanical properties of the joint because they usually have inferior physical characteristics, particularly fracture toughness [25, 26]. The hardness of these phases was not smaller than 195 HV in all joints brazed in this study (see Fig. 8). The crack path, after performing shear tests, follows the location of IMC in the majority of joints. In a few cases, where the crack path follows the interior of the braze, the thickness of IMC was not higher than 6 μ m. In fact, not only the hardness of IMC which has a strong effect on the joint performance, but also the thickness as well seems to play a vital role. Joints brazed with Ag–34Cu–2Ti and Cu–12Mn–2Ni filler metals were fractured at the interfacial areas, within the IMC, owing to the formation of a thick IMC in contrast to the joint brazed with Ag–27.25Cu–12.5In–

Fig. 9 Cross section of fracture surface (a) and fracture morphology (b) of the titanium/steel joint brazed at 750 °C for 15 min using Ag–27.25Cu–12.5In–1.25Ti filler metal



1.25Ti filler metal, which showed thin IMC at both interfacial regions. In other words, the fracture path follows the location of the IMC when its thickness is high enough to represent the weakest structure in the joint. Therefore, there is a critical thickness of the IMC layer for the maximum shear strength. At the critical IMC layer thickness, the shearing fracture occurred inside the braze. As the IMC layer thickness increases to the critical thickness, the fracture tends to occur at the substrate/IMC interface. This phenomenon is also reported in similar work [27].

During stress application in shear test, cracks originate at the IMC layer and propagate easily through it since it is brittle. An easy propagation of the crack leads to a decrease in the strength of the joint and the fracture morphology is likely to show brittle type behavior as in the case of joints brazed with Ag–34Cu–2Ti and Cu–12Mn–2Ni filler metals. In contrast, when the crack originates inside the braze, propagation becomes difficult due to the accumulation of stresses by the ductile structure. Hence, the joints record high strength and the fracture is likely to show ductile features as in the case of joints brazed with Ag–27.25Cu–12.5In–1.25Ti.

Conclusions

1. There is a strong relation between the thickness of IMC formed at the interfacial region, the values of shear strength of the joints, the location of the fracture or crack propagation, and the brazing temperature. The smaller the thickness of the IMC, the higher the shear strength. The average shear strength of the joint showed the highest values when brazed with silver-based Ag–27.25Cu–12.5In–1.25Ti at the temperature of 750 °C compared to joints brazed with Ag–Cu34–Ti2 and Cu–12Mn–2Ni filler metals at higher temperatures.
2. An increase in the brazing temperature led to an increase in IMC thickness.
3. The fracture path follows the location of the IMC when its thickness is high enough to become the weakest structure in the joint.

References

1. Lancaster FJ (1999) Metallurgy of welding. Abington Publishing, Cambridge, UK
2. Smith LS, Threadgill P, Gittos M (1999) Welding titanium— a designer and user handbook. TWI Report, Cambridge, UK, pp 1–15
3. Lathabai S, Jarvis BL, Barton KJ (2001) Mater Sci Eng A 299:81
4. He P, Zhang J, Zhou R, Li X (1999) Mater Charact 43:287
5. Baek S, Lee W, Koo J, Lee C, Jung S (2008) Mater Sci Forum 580–582:423
6. Sidiyakin VA, Pechenkin DK, Arbutov VM, Khaustov VS (2004) Weld Int 12:977
7. Qin B, Sheng GM, Huang GW, Zhou B, Qiu SY, Li C (2006) Mater Charact 56:32
8. Kurt B, Orhan N, Evin E, Calik A (2007) Mater Lett 61:1747
9. Smorygo O, Kim JS, Kim MD, Eom TG (2007) Mater Lett 61:613
10. Liu CC, Ou CL, Shiue RK (2002) J Mater Sci 37:2225. doi: [10.1023/A:1015356930476](https://doi.org/10.1023/A:1015356930476)
11. Huang X, Richards NL (2004) Weld J 83:73s
12. Kundu S, Ghosh M, Laik A, Bhanumurthy K, Kale GB, Chatterjee S (2005) Mater Sci Eng A 407:154
13. Szymlek K (2008) Adv Mater Sci 8:1730
14. Elrefaey A, Tillmann W (2009) J Mater Process Technol 209:2746
15. Elrefaey A, Tillmann W (2008) Weld J 87:113s
16. Elrefaey A, Tillmann W (2007) Metall Mater Trans A 38:2956
17. Elrefaey A, Tillmann W (2009) Brazing temperature determines the microstructure and mechanical behavior of steel/titanium brazed joints. IBSC, Orlando, FL
18. Voort GF (2004) ASM handbook, metallography and microstructures. ASM International, Materials Park, OH
19. Van Beek JA, Kodentsov AA, Van Loo FJJ (1995) J Alloys compd 217:97
20. Baker H (1992) ASM handbook: alloy phase diagrams. ASM International, Materials Park, OH
21. Shiue RK, Wu SK, Chen SY (2003) Acta Mater 51:1991
22. He P, Feng JC, Xu W (2006) Mater Sci Eng A 418:53
23. Petzow G, Effenberg G (1998) Ternary alloys: a comprehensive compendium of evaluated constitutional data and phase diagrams. VCH Verlagsgesellschaft, Weinheim, Germany
24. Gulay LD, Schuster JC (2003) J Alloys Compd 360:137
25. Murakami T, Nakata K, Tong H, Ushio M (2003) ISIJ Int 43:1596
26. Shiue RK, Wu SK, Shiue JY (2008) Mater Sci Eng A 488:186
27. Shin CK, Huh JY (2000) In: Third proceeding of EPTC 2000, pp 406–411