

Evaluate of braze joint strength and microstructure characterize of titanium-CP with Ag-based filler alloy

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ABSTRACT

This research investigates the influences of brazing parameters (temperature and time) on microstructures and the mechanical properties of commercially pure (CP) titanium sheet when it is brazed with CBS34 (Ag–20Cu–22Zn–24Cd) braze filler foil. Brazing was performed in a conventional atmosphere control furnace. The brazing temperatures and holding times employed in this study were 800–870 °C and 10–20 min, respectively. The qualities of the brazed joints were evaluated by ultrasonic test and the microstructure and phase constitution of the bonded joints were analyzed by means of metallography, scanning electron microscope (SEM) and X-ray diffraction (XRD). The mechanical properties of brazed joints were evaluated by microhardness and shear tests. The diffusion between Ti, Ag, Cu, Zn and Cd from substrate and braze alloy, developed a strong reaction between each other. A number of intermetallic phases, such as TiCu and Ti₂Cu in the Ag–Zn solid solution matrix have been identified especially at 870 °C – 20 min. Both the brazing temperature and the holding time are critical factors for controlling the microstructure and hence the mechanical properties of the brazed joints. The optimum brazing parameters was achieved at 870 °C – 20 min. Based on the shear test result, all cracks propagate along the brittle intermetallic compounds like Ti₂Cu in the reaction layer which typically are composed of quasi-cleavage (Ag–Zn matrix) and brittle appearance.

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1. Introduction

Titanium and its alloys play an important role in many modern industries (especially in aerospace and gas turbine engines), due to their highly desirable performance characteristics, such as good strength to density ratio, low density, high creep, fatigue and corrosion resistance [1–5]. This property has developed transition joints of Ti to other engineering materials such as steel, nickel, and copper-based alloys [7]. Many titanium joining methods, including welding, brazing and diffusion welding have been developed. Among those, brazing is widely applied in aerospace manufacturing for brazed titanium parts in aircraft frames (honeycombs structure) and engines [5]. Titanium has a strong chemical affinity (very reactive material) for oxygen and a stable and tenacious oxide layer forms rapidly on its surface in comparison to other metals. At temperatures above 500 °C, the oxidation resistance of

titanium decreases rapidly and it becomes highly susceptible to embrittlement by oxygen, nitrogen and hydrogen. Due to the fact that in titanium welding the temperature is more than 500 °C ($T_m^{Ti} \approx 1668$ °C), it is subjected to oxidation [1]. Titanium, in medical implants, public facilities, photocatalyst and industrial pipelines the adhesion of bacteria onto the surfaces of numerous materials can lead to the formation of biofilms and the outbreak of infectious diseases [6].

The advantages of titanium brazing in comparison with welding are: a decrease of energy and heat input, the decrease of residual stress, a lighter weight structure and the absence of a heat affected zone (HAZ). In titanium brazing technology, it is recommended that the brazing temperature does not exceed the α – β transformation temperature (usually 880–910 °C) in order to preserve the original microstructural and mechanical property of the Ti base metal [1–3,8]. With decreasing time or temperature of brazing, erosion of the substrate and excessive growth of intermetallic phase at the interface will be significantly decreased or eliminated [9]. As mentioned, in the brazing of Ti and its alloys, the brazing temperature should be as low as possible, in order to retard the grain growth in

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the base metal and joint parts. Since the brazing temperature is determined by the melting temperature of the filler alloy, many experiments have been done [5,10–13] on filler alloys with a decreased of the brazing temperature. One effective method of doing this is by adding alloying elements such as Cu, Zn, Mn, Be, and In to brazing fillers as well as producing fillers, in shapes of foil, powder, paste, or coat.

Other variables interfere with the brazing process such as the brazing temperature, holding time, braze alloy composition, filler metal thickness, and heating/cooling rate [14]. Other variables can interfere with the brazing process and play an important role. Furnace brazing in an inert gas or vacuum atmospheres is an ideal industry process for brazing due to its advantages [15,16].

(1) It is a method in which many variables (such as brazing temperature, time and atmosphere, and heating and cooling rate) can be easily controlled to ensure the repeatability of the process and guarantee a high-quality joint. (2) There is no requirement for skilled operators, flux, or post brazes cleaning. (3) Because a whole part is heated, distortion of the parts can be minimized or eliminated and (4) More than one joint per work piece can be brazed in a brazing cycle, but it requires an initial high cost investment and more energy for heating whole assembly.

Various brazing filler metal compositions have already been evaluated to braze Ti commercially pure (Ti-CP) [12,17,18]. Silver-based filler alloys have the advantage of a low melting point but there are several drawbacks such as the low strength and corrosion resistance in the joints when compared with titanium or zirconium based filler metals. The filler metal CBS34 (Ag–20Cu–22Zn–24Cd, wt.%), which has a similar composition to the BAg-2 (Ag–26Cu–21Zn–18Cd, wt.%) filler alloy according to American Welding Society (AWS) A5.8 [19], can definitely be considered as a potential solution for brazing titanium and its alloys. Copper, zinc and cadmium are the main reasons for the decrease in the melting temperature of the filler metal.

Elrefaey and Tillmann [12] evaluated the effect of brazing time and temperature on microstructure and mechanical properties of Ti-CP in vacuum furnace by Incusil-ABA (Ag–27.2Cu–12.5In–1.25Ti, wt.%) 200 μm filler foil, which had a melting range of 605–710 °C. The reported result for at a temperature of 800 °C under all holding times was not acceptable. However, high strength values have been achieved at a temperature of 750 °C and the maximum shear strength (92.3 MPa) was obtained at a holding time of 90 min. At a temperature of 710 °C, the brazed joint resulted in medium strength values. Several Ti–Cu intermetallic compound formations were the main cause for decreasing the strength. The predominant fracture morphology was described as a mixed dimple structure with tearing regions. This work focus on brazing Ti-CP at argon atmosphere as an inert gas and evaluate the effect of processing parameters (temperature and time) with Ag-based filler alloy (it has not been tested until now) on microstructure and mechanical properties. We investigated the joint mechanical properties by shear and micro hardness tests. The braze joint quality and microstructure were evaluated by an ultrasonic test, Light optical microscope (LOM) and scanning electron microscope (SEM)-EDS (Energy Dispersive Spectroscopy). Afterward, the fracture surface was analyzed with X-ray diffraction (XRD) and SEM.

2. Materials and design of experiments

2.1. Materials

The base metal used in this research was 1.5 mm thick Ti-CP with 890 °C $\alpha \rightarrow \beta$ transformation. 85 μm -thicks Ag-based (CBS34) has been selected as the brazing alloy. The nominal chemical composition of the base metal and filler are given in Tables 1

and 2, respectively. Single lap shear specimens with 10 mm width in the reduced cross-section were brazed with overlapping 4.5 mm (3T) according to the JIS Z 3192 [20] standard, by means of a wire-cutting machine. Also, the plate was cut into 10 mm \times 15 mm chips for microstructure analysis. The parent metals were first polished with SiC papers up to 600 grit and subsequently cleaned by an ultrasonic bath using acetone for 20 min at 50 °C as the solvent prior to furnace brazing. The brazing foils were cleaned in acetone before brazing and then sandwiched between the overlapping areas of the parent metals. The mechanical properties of Ti-CP base metal are mentioned in Table 3.

2.2. Fillers melting behavior

The melting behaviors of the filler foil were examined by a differential thermal analyzer (DTA, Shimadzu DTG-60H) from room temperature up to 900 °C at a heating rate of 20 °C/min in a dynamic atmosphere of air (20 ml/min). The melting ranges of the brazing filler metal are presented in Table 4.

2.3. Brazing condition

The schematic of atmosphere control furnace brazing (Iranian patent number: 72122) that was newly designed and used in this research is illustrated in Fig. 1. At first, the chamber was evacuated for about 10 min to approximately 1 mPa and then purged with high purity argon gas at a static flow which was controlled by a volume manometer. Through brazing, the samples were compressed and loaded by a 0.3 MPa pressure. Thermocouple (Chromel–Alumel) was connected to the samples proximity to the lap joint area (hot zone). Also, an ultra-high purity argon (99.999) was utilized throughout the heating/brazing/cooling cycle.

In conventional furnace brazing the cooling/heating rate could be adjusted to a maximum of 30 °C/min [16]. In titanium brazing, the cooling and heating rate must be as high as possible to reduce both excessive growth of intermetallic phase in the brazed joint and erosion of the substrate [21]. Hence it is important to reduce the brittle phases to assure the structure integrity by optimizing the brazing specification. Moreover, the quick cooling method should not be used because it creates thermal cracks and decrease the strength [14]. Therefore, it is essential to use a furnace that has high cooling/heating rate. The high heating rate was solved by using a 2500 W high power furnace. The highest cooling rate was achieved by introducing argon gas during the cooling part of the brazing cycle. Consequently, the heating and cooling rates during the brazing cycles were reached at 65 °C/min.

In the research done by Shiue et al. [13], a new cooling method for vacuum brazing was performed by quick cooling via filling the furnace with dry nitrogen and starting up the wind cooling system at the same time. This process for cooling samples is more expensive than the argon gas procedure we used in this investigation. This system is more economical and has industrial attraction. The joints were fixed with a steel clamp and then carefully placed into the furnace. The width of overlap was kept at 4.5 mm (3T) since it is recommended to use a lap width of no more than three times the thickness of the base metals in order to achieve high strength for the joint [22]. Elrefaey and Tillmann [22] proved that the average shear strength of the joint showed a general tendency to decrease

Table 1
Chemical composition (wt.%) of the Ti-CP.

Alloy	C	O	Fe	N	H	Ti
CP titanium	0.1	0.2	0.08	0.15	0.01	Bal.

Table 2
Chemical composition (wt.%) of the filler foil which used in this research.

CBS34 (L-Ag34Cd – Din 8513)			
Ag	Cu	Zn	Cd
34	20	22	24

Table 3
Mechanical properties of Ti-CP base metal.

Yield strength (Mpa)	Tensile strength (Mpa)	Elongation (%)
345	433	22

Table 4
Melting behaviors of the filler foil used in the experiment.

Filler braze alloys	CBS34
Solidus/liquidus temperature (°C)	610/705

with increasing lap width. It indicated that the average shear stress in the lap joint decreases and Von Mises stress was successfully utilized with the increase of the overlap width. As the overlap-length of joint increases, the Von Mises stress distribution becomes less uniform. The middle portion of the overlap contributes less to the overall load-carrying capacity of the joint, whereas the ends of the joint become overloaded. The non-uniform stress distribution in the lap joint causes the decreasing of the shear strength [23]. Table 5 summarizes all furnace brazing variables used in the experiment.

2.4. NDT of brazed joint

The ultrasonic test was carried out by the use of a probe which generated a longitudinal wave of 22 MHz in frequency. Measurements were performed on the “Krautkramer Branson” thickness measurement according to AWS-C3.8 [24], which is developed at the Iran air organization with a standard CL3 DL, transducer (Alpha, Aerotech) was attached to the surface of the brazed joint. To minimize the impact of contact pressure on the PAW amplitude, a thin layer of high-viscosity couplant was used.

2.5. Microstructure observation

Standard grinding and polishing sample preparation procedure was applied [25] and Kroll’s reagent (3 ml HF + 6 ml HNO₃ + 100 ml

Table 5
Summary of furnace brazing variables used in the experiment.

Brazing time (min)/temp (°C)	800	850	870
10	S/UT	S/M/UT/H	S/M/UT/H
20	S/M/UT	S/M/UT/H/X	S/M/UT/H/X

S: shear test specimen.
M: metallurgical observation specimen.
UT: ultrasonic test.
H: microhardness measurement.
X: XRD analyze.

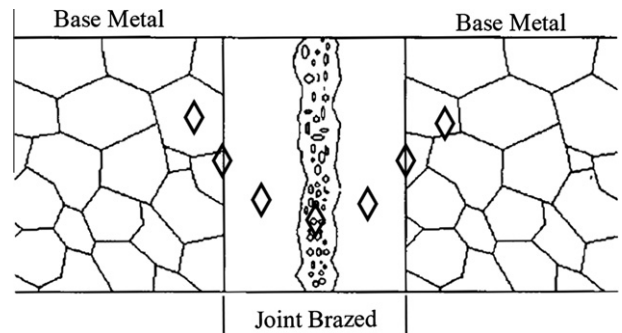


Fig. 2. Schematic representation of the profile microhardness testing.

H₂O) was used to evaluate the microstructures by a light optical microscope. The cross-section of the brazed specimens was examined using a VEGA/TESCAN scanning electron microscope, equipped with an energy dispersive spectroscopy (EDS) for element distributions, chemical and phase analysis. An Equinox 3000 (Inel, France) X-ray diffractometer (XRD) was applied for fracture analysis of the selected furnace brazed specimens. The Cu K_α was chosen as the X-ray source, and was operated at a voltage of 40 kV and a current of 40 mA with the scan range between 20° and 110°. The X-ray diffraction pattern was recorded and identified based on the powder diffraction file (PDF).

2.6. Mechanical testing

The shear test was performed using a Zwick/Reoll Hct 400/25 dynamic testing machine with a constant crosshead speed of 0.5 mm/min [7,8]. At least two shear test specimens were performed for each brazing condition. Failure analysis of the brazed specimen after the shear test was investigated using the SEM and EDS analyses. Micro hardness measurements were made using a micro hardness tester (Wolpert Instron) with a load of 100 g and

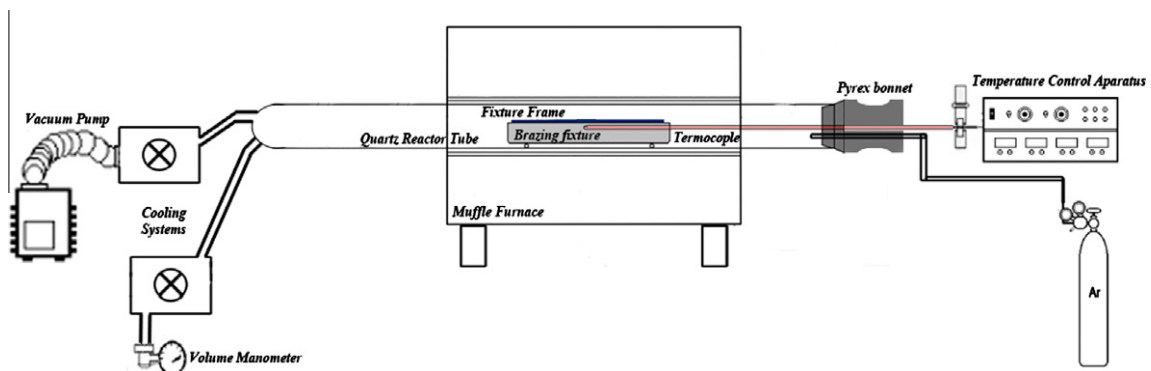


Fig. 1. Schematic of atmosphere control furnace for brazing.

a dwell time of 35 s. The details grid for micro hardness is illustrated in Fig. 2.

3. Results and discussion

3.1. Microstructure observations

Brazed joints were successfully formed in all the studied combinations of brazing temperatures and holding times. According to the ultrasonic test results, sound joints were obtained without any voids or cracks along joints only for samples brazed at 850 °C and 870 °C, as demonstrates in Table 6. Even though the brazing filler metal could melt at a brazing temperature of 800 °C which is higher than the temperature of the solidus and liquidus in the filler metal but evaporation of cadmium and some of zinc in the braze alloy established pores or voids in the brazed joint. Cd and Zn have low melting and boiling points [26]. Therefore, at higher temperatures, they evaporated and porosity remained in the joint. This result is in agreement with the ultrasonic tests according to Table 6. A typical form of this defect is shown in Fig. 3.

Fig. 4 shows SEM backscattered electron images (BEIs) of the furnace brazed at 850 °C for 10 min. Moreover, a quantitative overview of the chemical analyses (EDS) in atomic percentage for the different regions is provided in Table 7. Ag-rich liquid flows to the joint zone at an elevated temperature and it is responsible for filling the pores. Consequently, quantities of the voids have declined. There are three distinct layers observed at the braze joint, as shown in Fig. 4. At the titanium/brazed alloy interface, thin layers of β -Ti (Ti–Ag) phase were clearly distinguished in Fig. 4a. One of the main phases presented in the brazed area, region II in Fig. 4, is a Ti–Cu intermetallic phase containing low percentages of Ag and Zn. The stoichiometry of Cu/Ti ratio at this region is very close to Ti_2Cu . Migration of Ag, Cu, and Cd (strong β -stabilizing elements as noted in Table 8) in the titanium substrate lowers the eutectoid transformation temperature of Ti [27]. The presence of these alloying elements in a braze alloy is the main reason for the formation of Ti_2Cu phase at a lower temperature. The presence of alloying elements in a braze alloy decreases the brazing temperature and consequently affects the peritectic reaction temperature by consuming copper from braze alloy, especially with zinc. Finally, at region III, a matrix of Ag solid solution, rich in Cd and Zn, is present in high quantity with a low amount of titanium and copper through the brazed joint. The ternary Ag–Cd–Zn phase diagram [28] indicates that this phase is Ag-rich. Since there is no Ti content in filler alloy, it is expected that Ti atoms are transported from substrate via diffusion into the molten braze alloy.

SEM-backscattered electron images (BEIs) at a higher brazing holding time and temperature (Fig. 5) differed significantly from the sample which was brazed at 850 °C – 10 min. The composition of different phases at brazed joint has been determined by EDS analyses and is listed in Table 9. It is clear that a continuous reaction layer between the brazed seam and the titanium substrate was formed. In addition, the reaction layer has increased in thickness after the brazing temperature was prolonged. Different layers

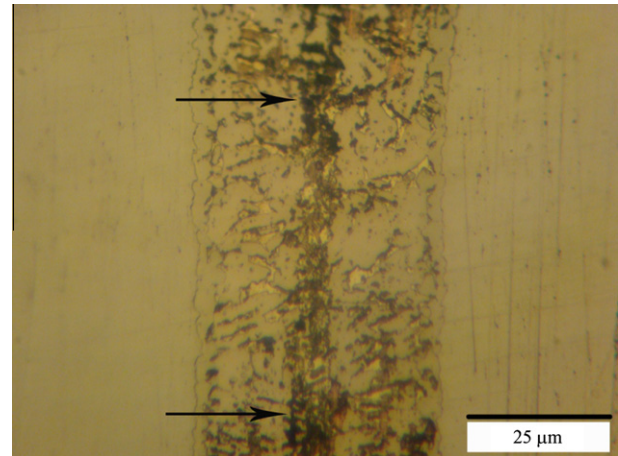


Fig. 3. Microstructure of brazed joint at 800 °C for 20 min. the pores were clearly observed and indicated by arrows.

of Ti–Cu intermetallic reaction layers appeared between the brazed alloy and titanium substrate, whose thickness of TiCu intermetallic phase increased after the brazing time or temperature, had been extended. The growth of the interfacial reaction layer resulted in the loss of elements in the braze alloy. According to the layers chemical analyses illustrated in Table 9 and the extrapolated data from Cu–Ti and Ti–Ag phase diagrams (Table 8) [28], both copper and silver preferred to solute in β -titanium. Afterwards, the solid solutions from these elements were able to be generated and the intermetallic compounds, such as Ti_2Cu , TiCu and/or TiAg, could be developed. In addition, the titanium diffusion from the titanium side toward the braze metal and the diffusion of Ag and Cu from braze alloy to titanium substrate were the main controlling factors to building these intermetallic phases. As shown in Fig. 5a and b, with increasing temperature and time, the Ag solid solution matrix contracted, owing to the release of Cu, to form more intermetallic phases with Ti. The chemical analysis of this region was lower in Ag compared to its equivalent region at a lower brazing time (region III). Fig 5c and d shows that interfacial reaction layers like β -Ti, Ti_2Cu , TiCu formed at high brazing times. They are labeled with 1, 2 and 3 respectively. Formation of region 1 is owing to the lower solubility of Ag in α -Ti than in β -Ti, as noted in Table 8. 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.

Titanium is strongly associated with Cu and forms a varied Cu–Ti reaction layers at the interface. Therefore, Ti_2Cu and TiCu formed at higher brazing times were thick and consumed most of the copper in the brazed zone. Increasing the soak time from 10 min to 20 min leads to an excessive growth of TiCu phase (see Fig. 5). Also this was displayed in another research [29]. It is stated elsewhere [30] that the growth rate of TiCu is much faster than that of Ti_2Cu in temperature above 850 °C. Accordingly, the minimum temperature and time needed to activate and generate TiCu phase in this research was 850 °C and 20 min, respectively. It could be

Table 6
Results of ultrasonic tests for brazed joints with CBS34 braze alloy.

Temp. (°C)	Time (min)	Layer thickness (mm)	Joint thickness (mm)	Results
800	10	1.49	1.49	Rej.
800	20	1.51	1.51	Rej.
850	10	1.5	3.05	Acc.
850	20	1.54	3.07	Acc.
870	10	1.5	3.11	Acc.
870	20	1.5	3.01	Acc.

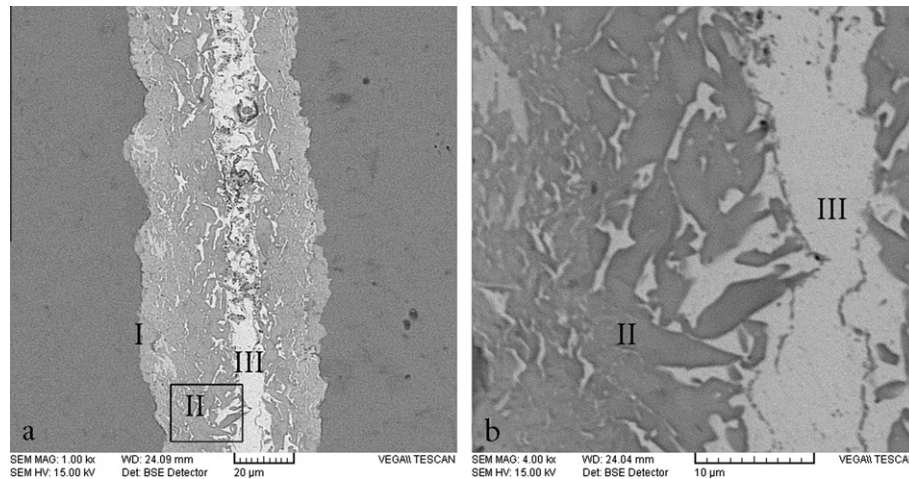


Fig. 4. SEM-BEIs of the brazed joints at 850 °C for 10 min (a), (b) closer view of the rectangular area in (a).

Table 7

Chemical analyses at regions shown in Fig. 4.

Symbol	Chemical analyses (at.%)					Probable phase
	Ti	Ag	Cu	Zn	Cd	
I	89.1	6.3	2	2.6	–	β -Ti
II	55.7	5.5	31.9	6.9	–	Ti ₂ Cu
III	1.2	84.5	0.8	4.2	9.3	Ag-rich

Table 8

Data extrapolated from Ti–Ag, Ti–Cu, Ti–Cd and Ti–Zn binary phase diagrams [25,27].

Alloy system	Maximum solubility in α -Ti		Maximum solubility in β -Ti	
	(at.%)	Temp. (°C)	(at.%)	Temp. (°C)
Ti–Ag	5	855	18	1300
Ti–Cu	1.6	790	13.5	1005
Ti–Cd	6.5	782	28.5	870
Ti–Zn	0	–	0	–

concluded that the higher brazing temperature caused the interfacial reaction during brazing. Also these phases developed when Ti–CP was vacuum brazed with Ag–27.2Cu–12.5In–1.25Ti filler foil [12]. Titanium and cadmium are proffered to solute in silver to form Ag solid solution matrix [28].

Therefore, by increasing the temperature and time of brazing, these elements would dissolve in each other. Afterwards, excessive Ti and Zn atoms were expelled from the Ag-matrix and generated intermetallic compounds, like TiCu and Ti₂Cu (labeled 4 and 5 in Fig. 5d), but were surrounded by a silver and zinc solid solution matrix. It is important to note that the Zn–Cu, Cd–Ag and Ag–Zn binary phase diagrams [28] show that silver is more soluble in cadmium and zinc when the temperature lowered. Likewise, the solubility of Zn in Cu is 39–32.5 wt.% at the temperature range of 454–902 °C. By decreasing the brazing temperature, which results in a higher cooling rate, these binary systems (Zn–Cu, Cd–Ag and Ag–Zn) create a condition for containing some intermetallic phase in our matrixes. Subsequently, the shape of TiCu phase would change from a continuous layer to globular particles with an increase of temperature or time. Region 6 is a poorer Ag–Zn solid solution matrix in contrast with region 5, which contain a Ti₂Cu intermetallic compound. The formation of interfacial TiCu and/or Ti₂Cu phase results in the isolation of the molten braze and Ti substrate [21].

3.2. Mechanical properties

Fig. 6 shows the mechanical properties of brazed specimens with various brazing conditions. The shear strength of joints revealed a general tendency to increase with an increase in holding time and brazing temperature. The best mechanical properties were achieved at a temperature of 870 °C and at a holding time of 20 min. They were equal to 164.2 MPa for shear strength and 5.6% for elongation. It is well known that the shear strength is ~ 0.6 of maximum tensile strength [31]. Consequently the optimum shear strength is 63% of the base metal (the strength of Ti–CP was 433 MPa according to Table 3). The maximum shear strength is approximately twice the amount of strength reached by Elrefaey and Tillmann [12]. From a microstructural point of view, the change of joint strength within the brazing parameters was to a large extent dependent on the joint microstructure. The thickness and type of the reaction layer and intermetallic phases in between the substrate and brazed alloy are critical factors in determining the strength of the joints. Titanium mainly reacted with copper in all joints and formed almost the same kinds of Ti–Cu intermetallic phases. It is obvious in Fig. 5a–d that with an increase in brazing temperature or time, the thickness of layers increased. It is suggested that the shear strength of the joint was influenced by the formation of the required reaction layer to achieve good strength for the brazed joint. The pores observed at a brazing temperature of 800 °C lowered the strength at this temperature. At the same time, the relative amount and percentage of the TiCu phase at a high temperature (870 °C) was very high compared to its content at lower temperatures (850 °C). For the specimen brazed at a temperature of 850 °C, the thickness of the reaction layer, especially β -Ti, was not enough to achieve a high strength for the joint. However, increasing the brazing time or temperature led to more wetting, interaction, or mutual diffusion at the interface, which reflected the high strength of the joint. Increasing the temperature to 870 °C led to an increase in the thickness of interaction layers, especially at a holding time of 20 min. The main reason for the increased shear strength and elongation is because of the nature of the microstructure (Fig. 5d). The formation of hard intermetallic compounds, such as TiCu and Ti₂Cu in a ductile of Ag–Zn solid solution matrix, creates a metal matrix composite, which is reinforced with TiCu and Ti₂Cu. Indeed, these intermetallic compounds act as second-phase particles, which prevent moving dislocation and slip planes [32]. Small second-phase particles, distributed in a ductile matrix, are a common source of

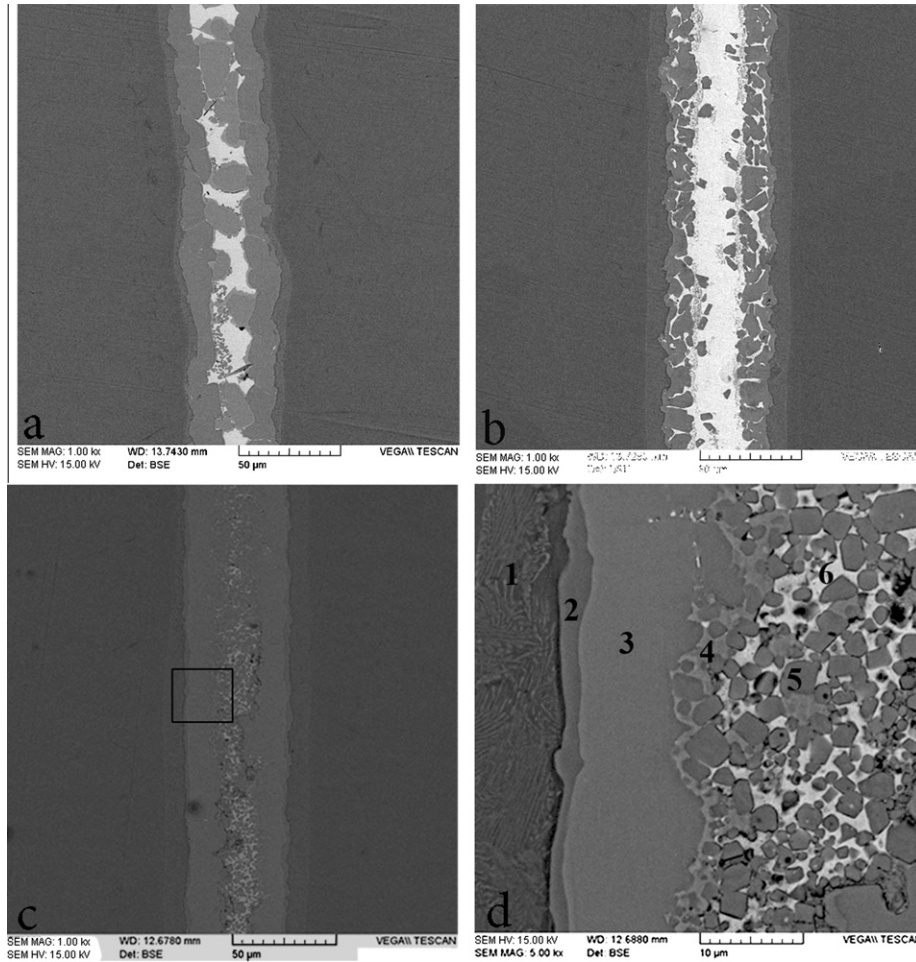


Fig. 5. SEM BEI of brazed joints: (a) 850 °C – 20 min; (b) 870 °C – 10 min; (c) 870 °C – 20 min and (d) closer view of the rectangular area in (c).

Table 9
Chemical analyses at regions shown in Fig. 5.

Symbol	Chemical analyses (at.%)					Probable phase
	Ti	Ag	Cu	Zn	Cd	
1	90	6.3	2	1.4	0.3	β-Ti
2	60.48	1.29	31	6.13	1.11	Ti ₂ Cu
3	49.3	2.46	42.8	4.9	0.64	TiCu
4	22	39.2	22.5	13.9	2.42	TiCu rich in Ag-matrix
5	41.3	16.7	27.2	11.8	2.99	Ti ₂ Cu rich in Ag–Zn matrix
6	42.3	12.8	25.5	14.8	1.67	Ti ₂ Cu rich in Ag-matrix

alloy strengthening. Furthermore, the globular shape of these precipitations is another reason for the increase in shear strength [31].

The profile of Vickers microhardness of different zones of the brazed joints is shown in Fig. 7. Fig. 4a shows which microstructure of specimen, brazed at 850 °C – 10 min, contained Ti₂Cu and Ag-rich phases. Fig. 7a shows that the microhardness value reaches 275 HV for Ti₂Cu and 105 for Ag-rich phases, (regions II and III) respectively. The increase in temperature and time of brazing is responsible for developing the TiCu intermetallic phase with the highest level of hardness (415 HV). Intermetallic compounds presented the highest hardness values at the interfacial region. The microhardness of the brazed joint at a temperature of 870 °C is shown in Fig. 7b. The microhardness indicates high values at the interfaces rather than the other areas, which is ascribed to the appearance of the TiCu phase. According to Fig. 5d, brazing at higher temperatures developed a thin layer of β-Ti between the base

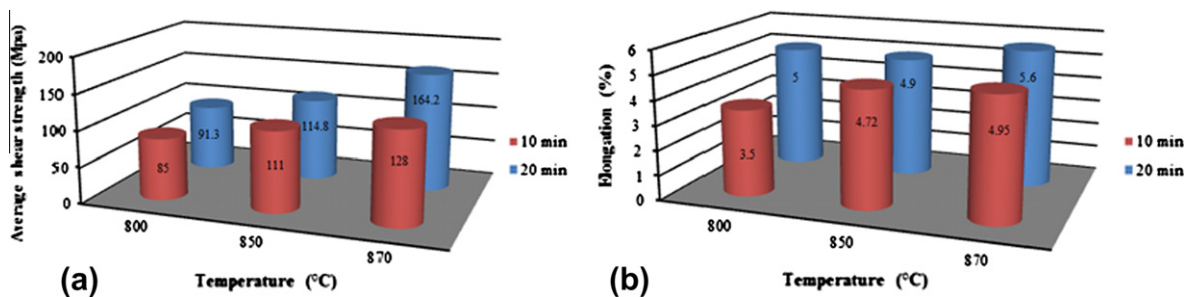


Fig. 6. Relation between (a) average shear strength and (b) elongation of the joint at different brazing temperature and time.

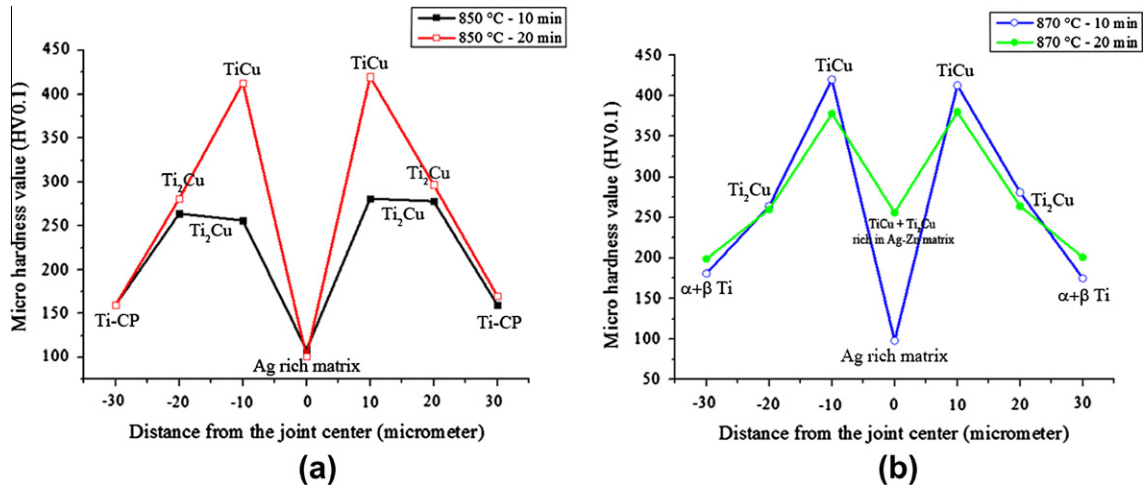


Fig. 7. Microhardness test of different zones of furnace brazed joint at temperature of 850 °C and 870 °C.

metal and reaction layers. Therefore the hardness value of this region (195 HV) is more than that of the Ti-CP base metal. Finally, brazing at 870 °C – 20 min established a microstructure of Ti₂Cu and TiCu precipitations surrounded by an Ag–Zn solid solution matrix (regions 4, 5 and 6 in Fig. 5d). It is important to note that the specimen which brazed at 870 °C – 20 min has uniform distribution hardness in comparison with the other ones, which is due to the increase in shear strength.

Fig. 8 shows that the joints failed mainly at the center of the braze alloy or interface at all brazing temperatures. The fracture path follows the interior of the braze alloy, mainly through the silver solid solution phase. With increased time and temperature, the fractured path is moving from the Ag-rich matrix to the interface due to the stronger bond between them. This implies that the TiCu intermetallic compound is a more harmful phase in comparison with the Ti₂Cu phase. Fig. 9 shows the SEM fractograph and EDS results (Table 10) for different regions of the fractured surface. Many cracks indicated by the arrows (Fig. 9a and b) are initiated from the

brittle Ti₂Cu phase. The Ag–Zn matrix phase shows that quasi-cleavage appearance, as shown in Fig. 9c and d next to the brittle Ti₂Cu phase. Similarly, the quasi-cleavage dominated fractures of the Ag–Zn matrix contained in the TiCu phase are widely observed in Fig. 9e. Accordingly, the quasi-cleavage fracture is favorable for the strength of the joint. The intermetallic compound formed at the titanium/braze interface reduced the strength of a bonded joint and caused the brittle fracture.

Furthermore, to confirm the presence of different phases especially those directly at the fracture surface, XRD from fractured surfaces at brazing temperatures of 850 °C and 870 °C for 20 min were analyzed as it is shown in Fig. 10. XRD not only confirmed the presence of Cu–Ti intermetallic compounds such as TiCu and Ti₂Cu, but also suggested the presence of different AgTi and Ag–Zn phases at the fracture surface. For the specimen brazed at 850 °C – 20 min (Fig. 10), dominated Ti₂Cu intermetallic phase were found at the fractured surface. Increasing the brazing temperature to 870 °C at the same time developed an Ag–Zn phases in accordance with

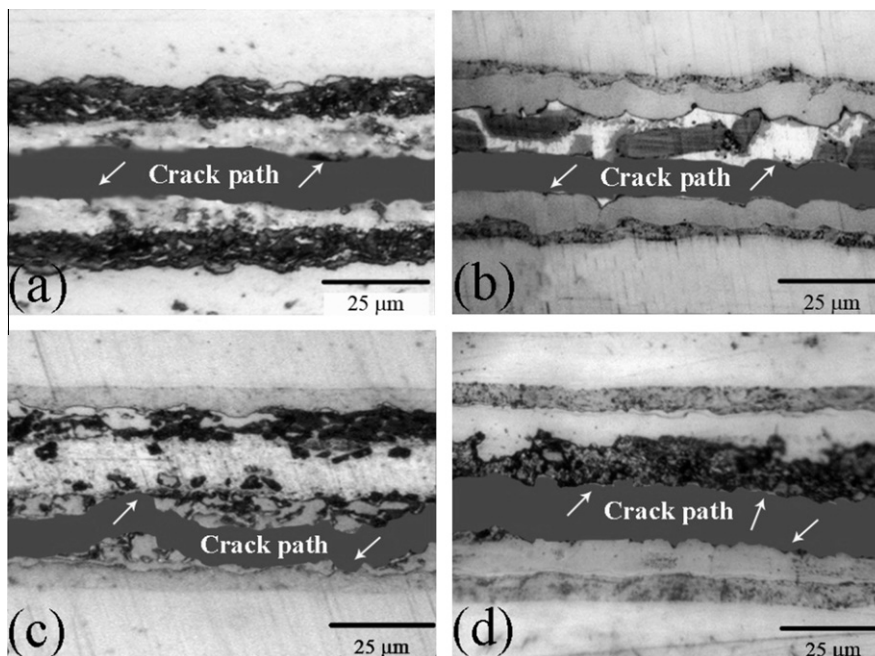


Fig. 8. Fracture paths after performing the shear test where (a) 850 °C – 10 min, (b) 850 °C – 20 min, (c) 870 °C – 10 min and (d) 870 °C – 20 min.

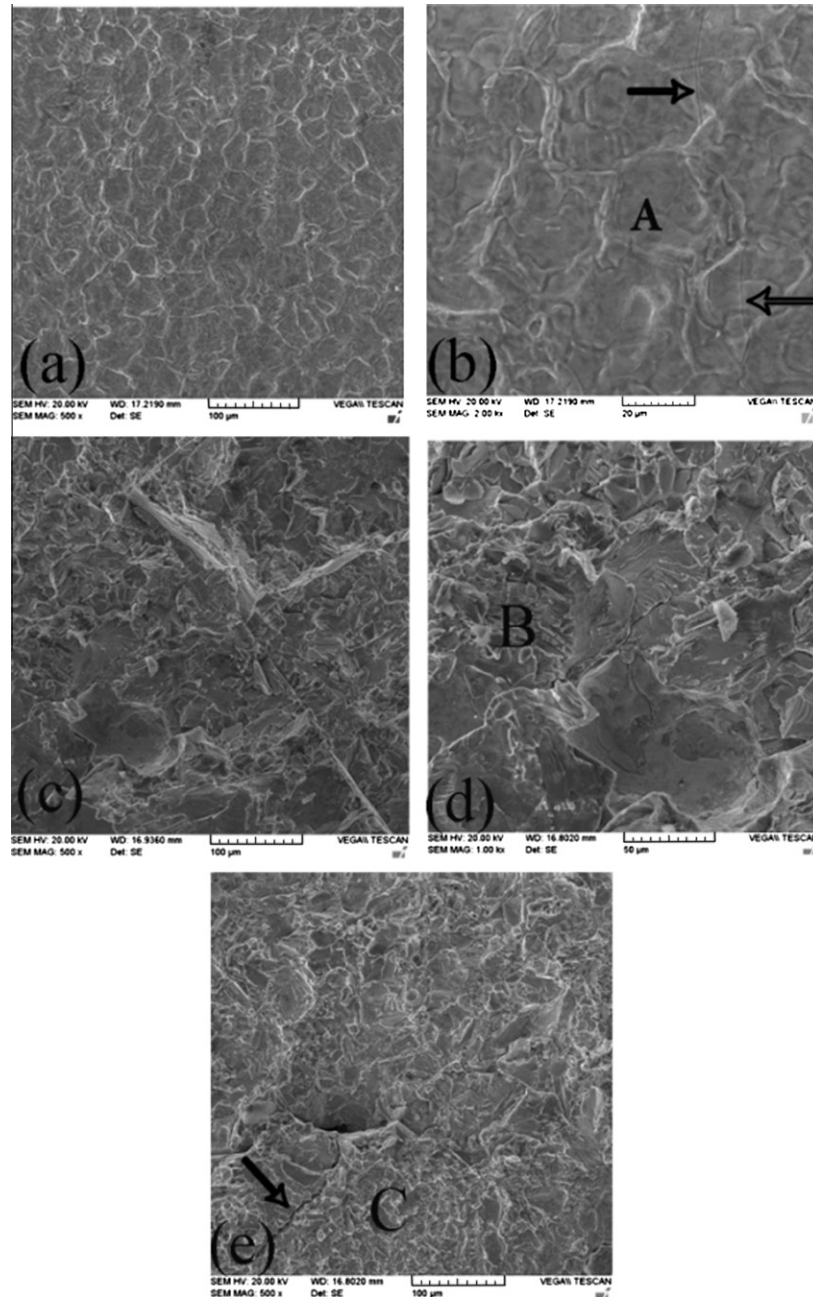


Fig. 9. Fracture morphology for brazed sample at (a and b) 850 °C – 20 min, (c and d) 870 °C – 10 min and (e) 870 °C – 20 min; arrows are indicated to crack growth.

Table 10

Chemical analyses at regions shown in Fig. 9.

Symbol	Chemical analyses (at.%)					Probable phase
	Ti	Ag	Cu	Zn	Cd	
1	51.3	8.2	31.9	6.3	2.3	Ti ₂ Cu
2	41.3	13.5	27.2	14.8	3.2	Ti ₂ Cu rich in Ag–Zn matrix
3	46.4	4.5	33.6	14.7	0.8	TiCu rich in Ag–Zn matrix

Ti₂Cu intermetallic compound. The existence of the Ti₂Cu phase and the Ag–Zn solid solution matrix in the specimen brazed at 870 °C leads to the occurrence of quasi-cleavage fracture instead of the brittle-dominated fracture type, as was observed in the specimen brazed at 850 °C.

4. Conclusion

Commercially pure titanium has been successfully brazed using CBS34 in an atmosphere control furnace. The microstructural evolution and bonding strength were experimentally assessed. The conclusions are summarized as follows:

- (1) The joint mainly consists of β-Ti, Ti₂Cu and Ag-rich phases at 850 °C – 10 min. The amount of Ti₂Cu decreases with increasing brazing temperature and/or time due to the diffusion of Cu atoms from the braze alloy into the Ti substrate which developed Ti₂Cu and TiCu intermetallic in an Ag–Zn solid solution matrix. These phases were detected and confirmed by XRD analyses depending on the employed brazing parameters.

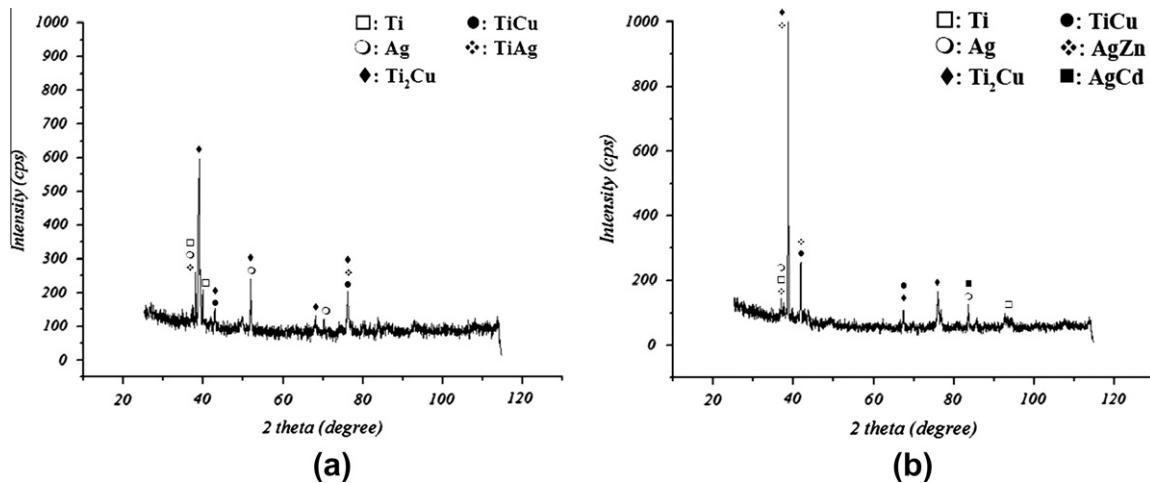


Fig. 10. XRD from fractured surfaces at brazing temperatures of 850 °C (a) and 870 °C (b) for 20 min.

- (2) At the same time, the shear strength of joints revealed a general tendency to increase with an increase in holding time. When the brazing temperature was increased to 870 °C, the joint mainly comprised of β -Ti, Ti_2Cu and TiCu rich in Ag-Zn matrix.
- (3) Joint furnace brazed at 870 °C – 20 min demonstrates the highest shear strength up to 164.2 MPa which is 63% strength of base metal. Microhardness measurements showed that TiCu phases are more hardened than Ti_2Cu phases. Brazing at 870 °C – 20 min established uniform distribution hardness rather than the other brazing temperatures.
- (4) High shear strength joints were fractured at the interface of the brazed alloy with substrate mainly in the Ag-Zn solid solution matrix and the fracture morphology for those kinds of joints presented quasi-cleavage characteristic.

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