Association of Metallurgical Engineers of Serbia
AMES

Scientific paper
UDC: 620.163.1:669.295 ;
620.163.1:669.14.018.8

DIFFUSION BRAZING OF TI-6AL-4V AND STAINLESS STEEL 316L USING AGCUZN FILLER METAL

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Received 21.04.2013
Accepted 08.05.2013

Abstract

In the present study, vacuum brazing was applied to join Ti-6Al-4V and stainless steel using AgCuZn filler metal. The bonds were characterized by scanning electron microscopy, energy dispersive spectroscopy and X-ray diffraction analysis. Mechanical strengths of the joints were evaluated by the shear test and microhardness. It has been shown that shear strength decreased with increasing the brazing temperature and time. The wettability of the filler alloy was increased by enhancing the wetting test temperature. By increasing the brazing temperature various intermetallic compounds were formed in the bond area. These intermetallic compounds were mainly a combination of CuTi and Fe-Cu-Ti. The shear test results verified the influence of the bonding temperature on the strength of the joints based on the formation of different intermetallics in the bond zone. The fracture analysis also revealed different fracture footpath and morphology for different brazing temperatures.
Keywords: Diffusion brazing; Titanium alloy; Stainless steel; Filler metal.

Introduction

The titanium alloys and stainless steels used in the aerospace and shipbuilding industries are needed to be joined due to their excellent corrosion resistance and high strength to weight ratio [1]. There are some works on the joining of these alloys emphasizing the application of different bonding techniques such as diffusion bonding and explosion welding, but most of the joints revealed poor bonding characteristics due to the formation of brittle intermetallic compounds [2]. The intermetallics were unavoidably produced by the reaction of the elements in the base alloys. The effect of

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brazing parameters on the microstructure and mechanical properties of the joints showed that the joining of the titanium alloys should be performed in a high - vacuum environment with severe control to avoid the reaction of the titanium with other elements [3]. It is also reported that numerous brazing filler metal compositions can be applied to join titanium alloys and stainless steels. Most of these filler metals have a melting temperature above the beta transus temperature where is the critical temperature for α to β phase transformation [4]. The significant differences of physical-chemical properties of the interlayer and base materials can lead to chemical, mechanical and structural heterogeneities. In the case of diffusion bonding, due to the limited solid-solubility of Fe, Cr, Ni and Ti, the bonding temperature plays a critical role in the formation of intermetallic phases, which may deteriorate the mechanical properties of the joints [5,6]. Compared to Ni and Ti-based filler metals, Ag-based filler metals have the advantage of a relatively low diffusion brazing temperature [7,8]. Moreover, addition of Ti to the filler metal increases the wettability of the filler material on the stainless steel due to the diffusion of titanium across the interface [9,10].

In the present investigation, the microstructural development of the alloys during the diffusion brazing were investigated and the mechanical properties of the bonds were analyzed. The study was coupled with the study of the wetting of the filler alloy on the base for different bonding time.

Experimental procedure

The stainless steel 316L and Ti-6Al-4V were cut to pieces with the dimension of 55×40×2 mm. In addition, the filler metal was in the form of a foil with the thickness of 150 μm. Chemical composition and mechanical properties of the materials are listed in Table 1 and Table 2, respectively. For the wetting experiment the filler alloy was placed on the substrates in the semi-spherical form. Each of the filler half-ball had a weight of around 0.1 *g*. All specimens were cleaned for 22 min in an ultrasonic bath using acetone. The wetting test was carried out in a vacuum furnace (ADAMLE LHOMARGI, France) with the pressure of 5×10^{-6} mbar at 700 ºC- 860 ºC for 5 to 60 min. After the wetting experiment, the brazing process of the materials was carried out at 800 ºC, 830 ºC and 860 ºC for 5, 15 and 30 min, respectively. The heating rate was set to be about 10 (*ºC/min*). The cross section of the bonded titanium/steel joints were prepared by standard polishing techniques and subsequently etched with some etchant solutions as listed in Table 3. The phases formed during the bonding process were characterized by scanning electron microscopy (SEM), using a CamScan MV2300 operating at 20 KV equipped with energy dispersive spectroscopy (EDS) for the chemical analysis. Moreover, SEM was used to examine the fracture surface of the shear specimens. X-ray diffraction (XRD) analysis was carried out to identify the phases formed during the bonding process after performing the shear test. The Cu K_α was chosen as the X-ray source. The X-ray scan rate was set at 4 *deg/min* in the range of 20 and 120 *deg*.

Table 1. Chemical composition of the materials.

Material	Chemical composition (wt.%)											
	Ti	Al	V	Fe	C	Mn	Cr	Mo	Ni	Ag	Zn	Cu
Titanium alloy (Ti-6Al-4V)	Bal.	5.5	4.5	-	-	-	-	-	-	-	-	-
Stainless steel (316 L SS)	-	-	-	Bal.	0.03	2.0	17.0	2.0	12.0	-	-	-
Filler alloy (AgCuZn)	-	-	-	-	-	-	-	-	-	Bal.	25	25

Table 2. Mechanical properties of the base metals and filler metal.

Material	Yield Strength (MPa)	Tensile Strength (MPa)
Titanium alloy (Ti-6Al-4V)	830	900
Stainless steel (316 L SS)	190	600
Filler alloy (AgCuZn)	350	430

Table 3. Chemical composition of the etchants.

Materials	Chemical Composition
Ti-6Al-4V	80 ml ethanol + 2 ml HF + 20 ml HNO_3
316L SS	10 ml HNO_3 + 5 ml HCl + 0.1 g $CuCl_2$

The specimens for the tensile test coupans were machined according to AWS C3.1-63. Fig.1 shows a specimen for the tensile test. The overlap of the bond area was set 6 mm or *3*t* (*he thickness of the specimen)*) for all experiments. The joints were fixed with a stainless steel clamp and then carefully placed in a vacuum furnace. The shear test was carried out with the rate of 0.5 (*mm/min*). For each shear test three specimens were used to validate the results of the test. The hardness measurement was performed with a Vickers microhardness testing machine with 200 *g* load.

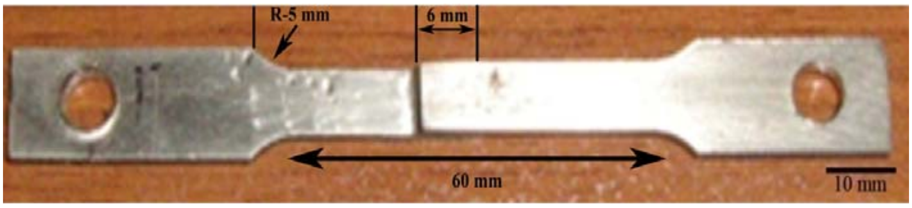


Fig. 1. Shear test specimen after the bonding process.

Results and discussion

Wettability observations

Fig.2 shows the wetting angle of both Ti-6Al-4V and 316L stainless steel substrates with AgCuZn braze alloy. This figure shows that the wettability of the AgCuZn braze alloy on both substrates was improved by increasing the brazing temperature and time as the wetting angle was considerably decreased. By increasing the brazing temperature and time atomic diffusion and alloying of the base metal and braze alloy were increased. In addition, wetting of Ti-6Al-4V was better than 316L stainless steel with AgCuZn braze alloy.

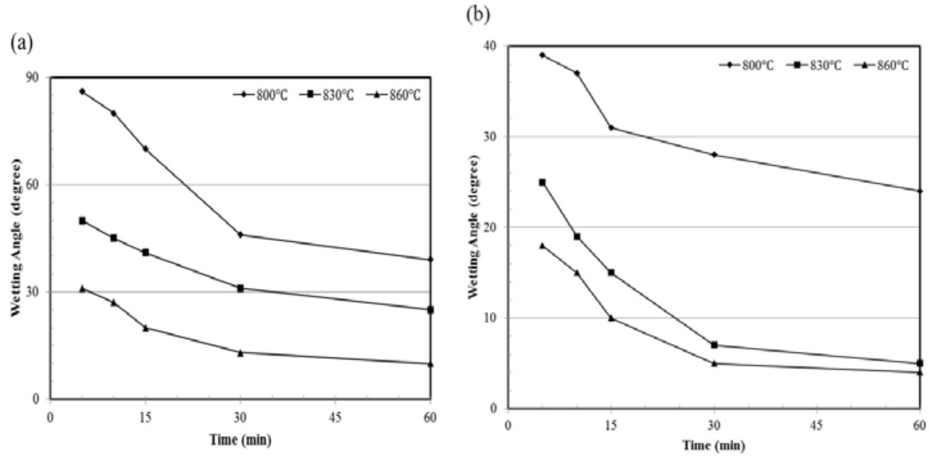


Fig. 2. Wettability of the AgCuZn braze alloy on the (a) stainless steel 316L and (b) Ti-6Al-4V.

The wettability of 316L stainless steel decreases due to the presence of a thin chromium oxide layer. However, titanium as a very reactive element can react and wet with the braze alloy. AgCuZn braze alloy did not show decent wettability on both Ti-6Al-4V and 316L stainless steel at 800 ºC. The wetting angle was greater than 90 º at 800 ºC on the titanium alloy substrate (see Fig.3). On the other hand, the braze alloy was detached from the stainless steel after the wetting test. There was not any bond for the AgCuZn braze alloy on the stainless steel. The reason might be attributed to a very short time used for the wetting test. The time and temperature was not sufficient to carry out an elemental reaction between the two materials. Moreover, it is probable that the adhesion force cannot conquest the surface energy of the materials. In addition, existence of zinc in the AgCuZn braze alloy can affect wetting and decrease the wettability. It has been understood that the reason of improving the wettability with increasing the brazing temperature and time is due to more elemental reactions.

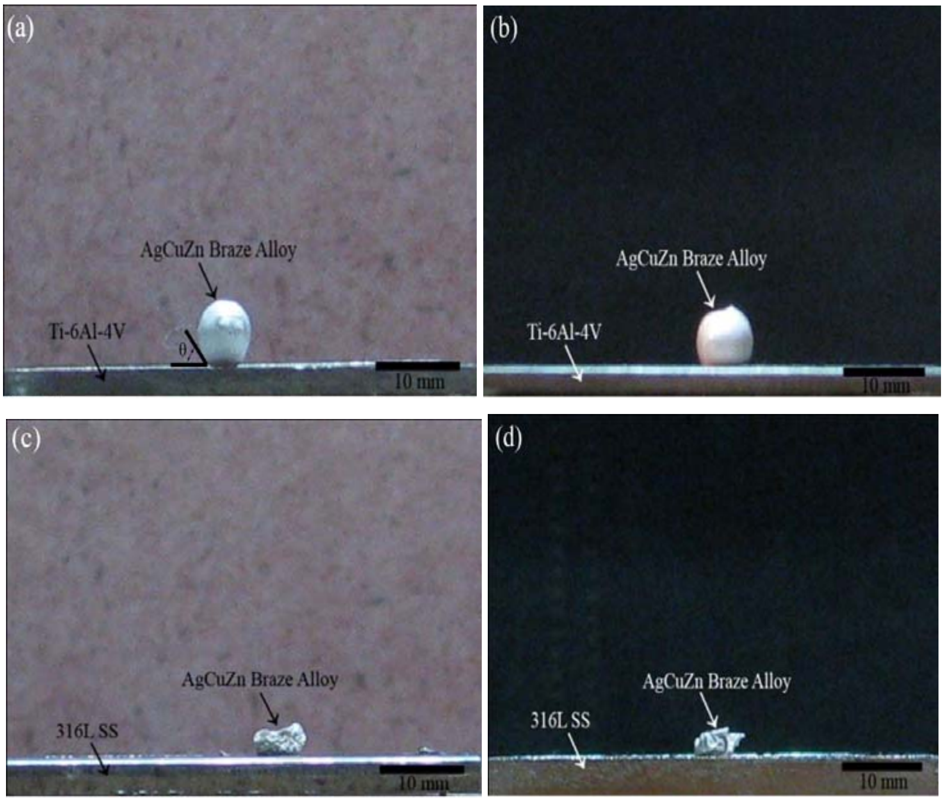
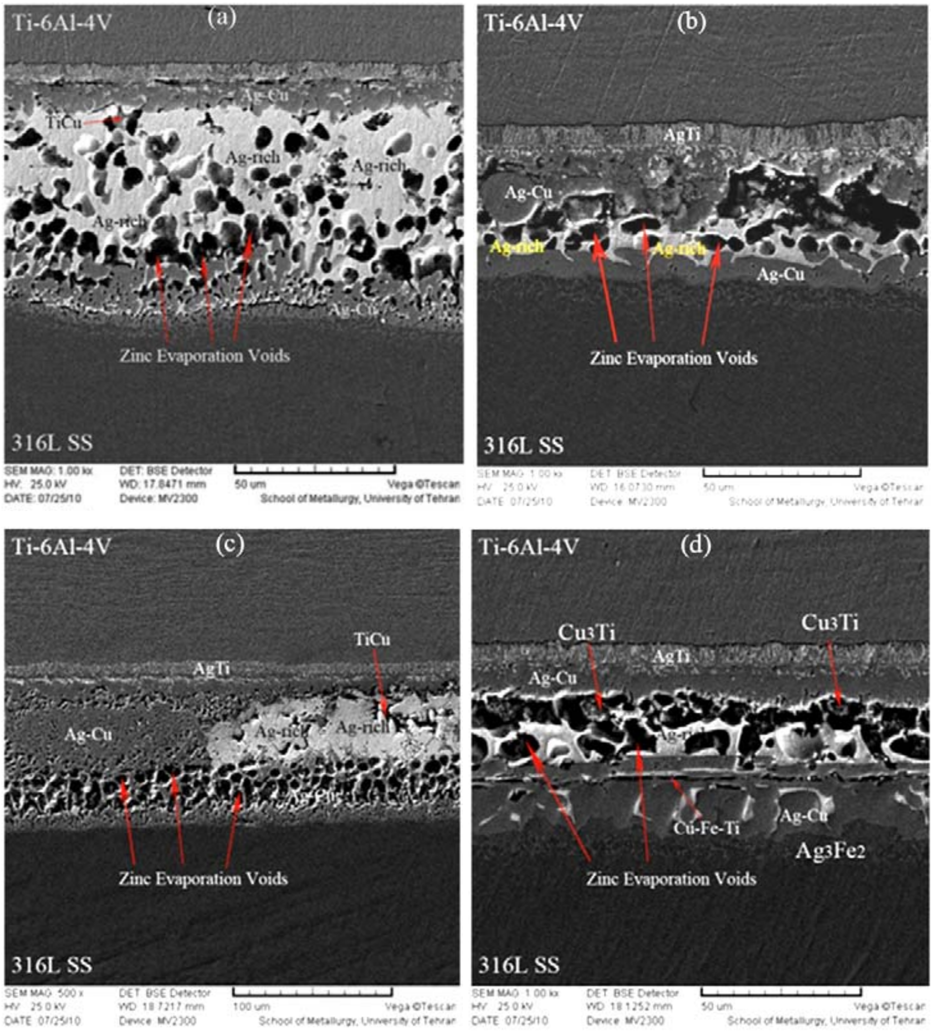


Fig. 3. Wettability of the filler alloy on the Ti-6Al-4V at (a) 700 ºC for 60 min and (b) 750 ºC for 60 min and stainless steel at (c) 700 ºC for 60 min and (d) 750ºC for 60 min.

Microstructural development during the bonding process

Fig.4 shows the scanning electron microscopy images (SEM-BSE) of the joint cross section. According to this figure, some reaction layers were formed on the shared surface of the base metals and interlayer. EDS analysis of the interface layer shows that the light-color phase in Fig.4 is Ag-rich phase. The magnitude of Ag-rich phase decreased with increasing the brazing temperature and time.


Ti-6Al-4V
(a)
Ag-Cu
TiCu
Ag-rich
Ag-rich
Ag-rich
Ag-Cu
Zinc Evaporation Voids
316L SS
SEM MAG: 1.00 kx
DET: BSE Detector
50 um
Vega ©Tescan
HV: 25.0 kV
WD: 17.8471 mm
DATE: 07/25/10
Device: MV2300
School of Metallurgy, University of Tehran
Ti-6Al-4V
(b)
AgTi
Ag-Cu
Ag-rich
Ag-rich
Ag-Cu
Zinc Evaporation Voids
316L SS
Ti-6Al-4V
(c)
TiCu
AgTi
Ag-Cu
Ag-rich
Ag-rich
Zinc Evaporation Voids
316L SS
SEM MAG: 500 x
100 um
Ti-6Al-4V
(d)
Cu3Ti
Cu3Ti
AgTi
Ag-Cu
Cu-Fe-Ti
Ag-Cu
Ag3Fe2
Zinc Evaporation Voids
316L SS

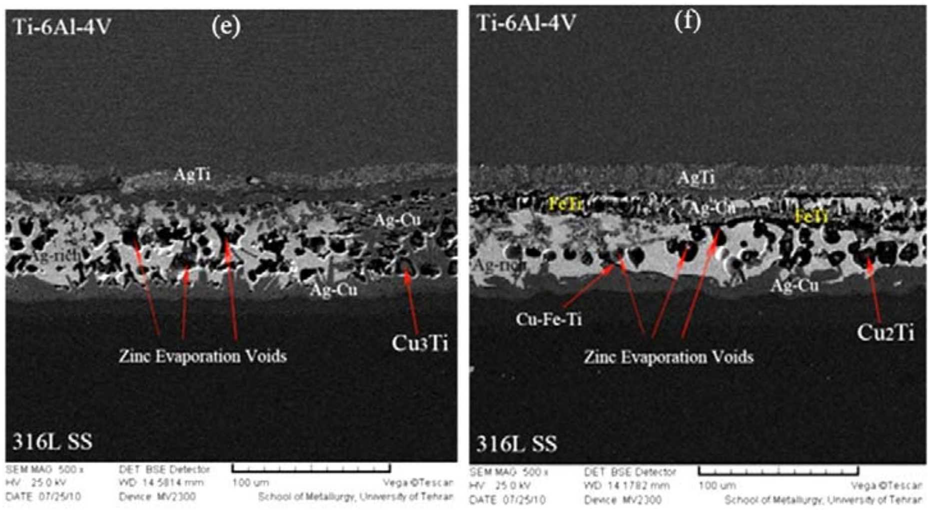


Fig. 4. Microstructural observation of the AgCuZn braze alloy by SEM.

The Fig.4 also shows that the Ag-rich phase is replaced with Cu_2Ti, Ag_3Fe_2, FeTi and Fe-Cu-Ti intermetallic compounds with increasing the brazing temperature and time. Moreover, some cavities can be seen in the joint area. Probably they originated from vaporized zinc content in the braze alloy. There was not any cracks in the brazed joint at any of the brazing conditions. Lack of the crack may be due to the high wettability and the capillarity effect of Ag-rich phase. The existence of a soft phase, such as Ag-rich phase, caused the residual stress in the joint to decrease. Namely, the existence of the Ag-rich phase around a very brittle intermetallic compound such as Fe-Cu-Ti at 860 ºC for the holding time of 30 min can prevent cracking. In addition, on the surface of Ti-6Al-4V and AgCuZn braze alloy the AgTi intermetallic compound was formed as a continuous layer at any of the brazing conditions except for the brazing at 800 ºC for 5 min. As the AgTi phase is a soft intermetallic compound it is not very destructive for the brazed joint. The Fe-Cu-Ti brittle intermetallic compound was formed at 830 ºC and 860 ºC for the holding time of 30 min. It is notable that the Fe-Cu-Ti brittle intermetallic compound was formed just in 30 min. The reason might be due to the presence of 150 μm thick foil of AgCuZn. This thick layer can act as a barrier and prevent the diffusion of Ti and Fe in the joint area when the brazing time is shorter than 30 min. However, for the completed brazing time of 30 min the AgCuZn filler metal cannot be a barrier and the Fe-Cu-Ti brittle intermetallic compound was produced.

Fig.5 shows the XRD results of the brazed joints. For the XRD analysis, the fractured surface of the brazed joints was used. The beam diameter of X-ray was about 1 mm and the width of the brazed joints was about 150µm. As it is seen there was consistency of the results achieved by XRD and EDS chemical analysis.

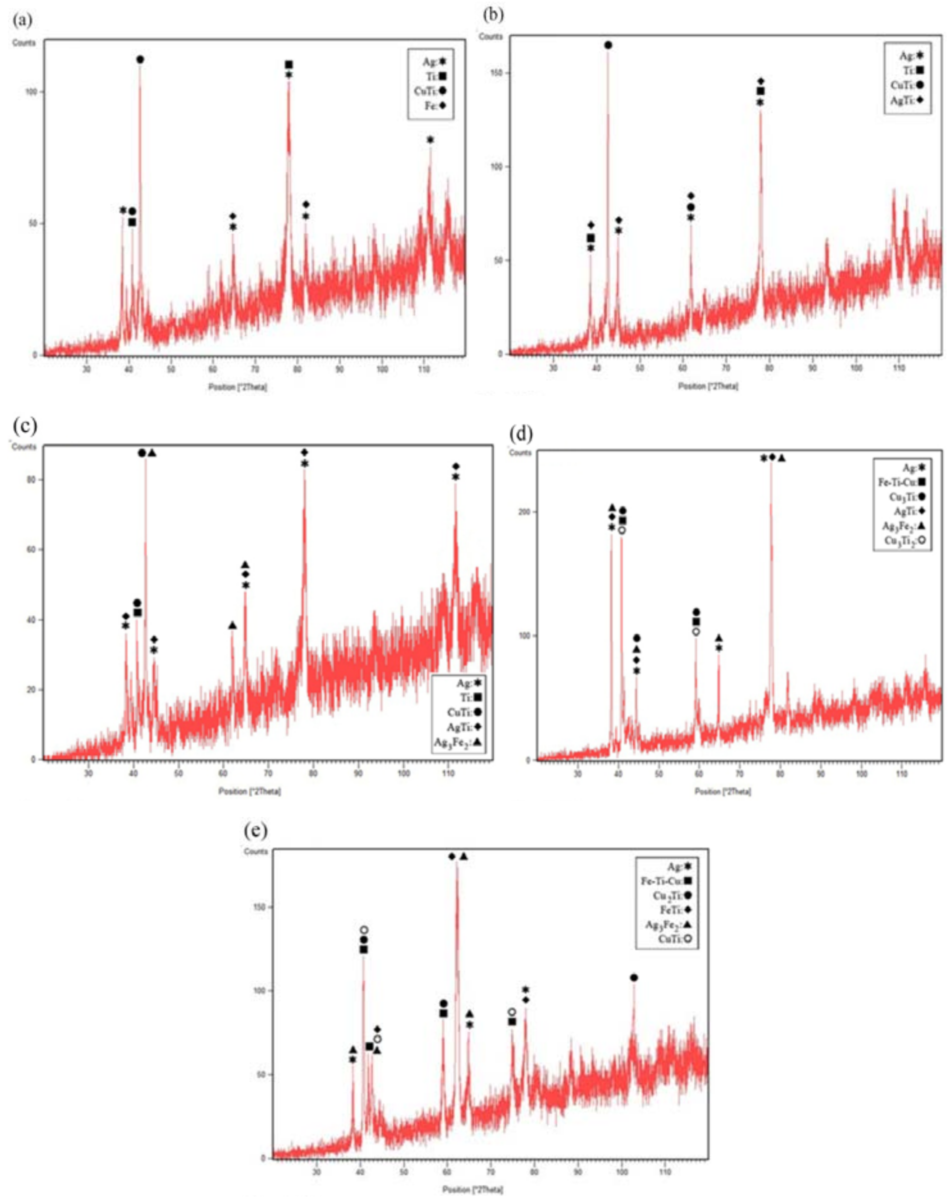


Fig.5. XRD analysis of the brazed joints prepared at a) 800 ºC, 5 min; b) 800 ºC, 15 min; c) 800 ºC, 30 min; d) 830 ºC, 30 min and e) 860 ºC, 30 min.

It was reported that in the vacuum brazing of Ti-6Al-4V and stainless steel, some reaction layers can be formed in the substrate/braze alloy interfaces and also the Fe-Cu-Ti intermetallic compound can be formed at the interface. It was also reported that for the brazing of a titanium alloy and steel using Incusil-ABA® interlayer the TiCu intermetallic can be formed at the brazing temperatures higher than 750 ºC [3].

According to Fig.4, the Fe-Cu-Ti intermetallic compound was formed at 316L stainless steel/AgCuZn interface. The Cu-Ti intermetallic compound was produced upon increasing the brazing temperature. Therefore, the results of this study with AgCuZn filler metal are consistent with those of Elrefaey and Tillman [3] and Liu *et al*. [11].

Results of shear strength tests

Fig.6 shows the shear strength of the brazed joint with the AgCuZn filler metal. Shear strength was achieved in the range of 48-85 MPa. The study showed that the shear strength decreased with increasing the brazing temperature and time. For the bonds prepared at 860 ºC for 30 min, joint shear strength decreased significantly. It may be caused by increased amount of Fe-Cu-Ti brittle intermetallic compound and existence of brittle intermetallic compounds such as FeTi, Cu_2Ti in the interface (see Fig.5e). As the silver base phases are soft and flexible, the embrittlement of the Cu-Fe and Cu-Ti intermetallic compounds were noticeably reduced. The brazing temperature has a critical role in the formation of the reaction layers. By increasing the brazing temperature, diffusion coefficient increases and higher reaction energy would be produced. Higher reaction energy can give rise to producing higher amount and variety of brittle intermetallic compounds. The intermetallic compounds higher brittleness would result in producing the lower joint shear strength. In addition, as described earlier, for the brazing time of 30 min, the AgCuZn braze alloy cannot play its role as a barrier layer to prevent the reaction between Fe and Ti.

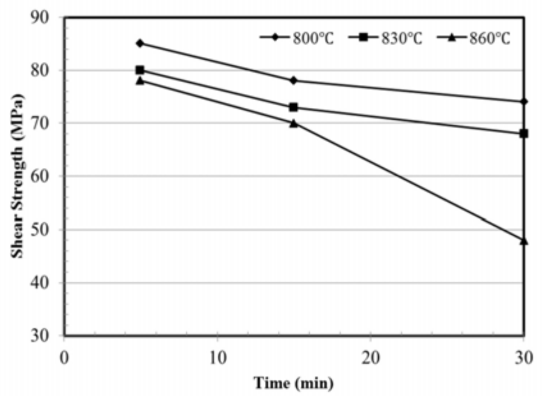
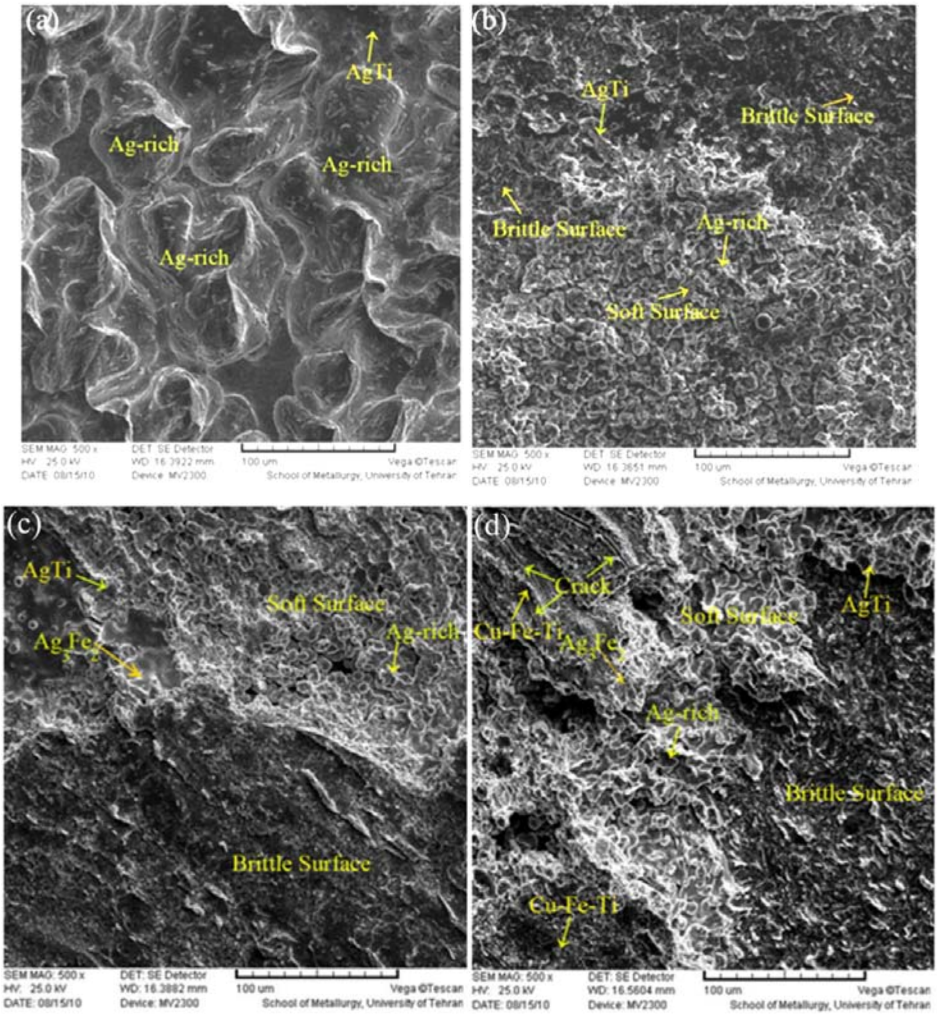


Fig.6. The shear strength of the joints prepared by AgCuZn braze alloy at different bonding temperatures.

Abdel *et al*. [12] reported that in brazing of CP Ti and low carbon steel with Ag-based braze alloy, shear strength was in the range of 25-50 MPa. Furthermore, they reported that with increasing brazing temperature, the shear strength tends to be decreased. The result of the shear strength for the present investigation shows the same trend in the reduction of the shear strength of the bonds prepared at different temperatures. However, in this study the value of shear strength is about 30 MPa greater than that achieved by Abdel *et al*. [12]. Fig.7 shows SEM-SE images of the fractured surfaces after the shear test. In all specimens, fracture occurred in the joint interface. It should be noted that the Ti-6A-4V side was used for the fractography study. Fig.7a shows a ductile fracture which indicates the effect of the silver on the formation of the fracture cracks as the fracture was slightly slow. By increasing the brazing temperature and time the ductile fracture area was decreased and was replaced with the brittle fracture surface. For the bonds prepared for 30 min at 860 ºC (Fig. 7e) the ductile fracture area decreased significantly and the brittle fracture played a significant role in the fracturing mechanism. As it was described in Fig.4, at low temperatures the soft Ag-rich phase covered a wide area of the brazed joint; however, with increasing the brazing temperature and time the amount and variety of the intermetallic compounds were increased. Fig.4 showed that with increasing the brazing temperature and time the amount of the soft compounds were decreased and they were replaced by the brittle compounds. Hence, it is clear that the fracture mode should be changed from ductile to brittle by increasing the brazing temperature and time [13].



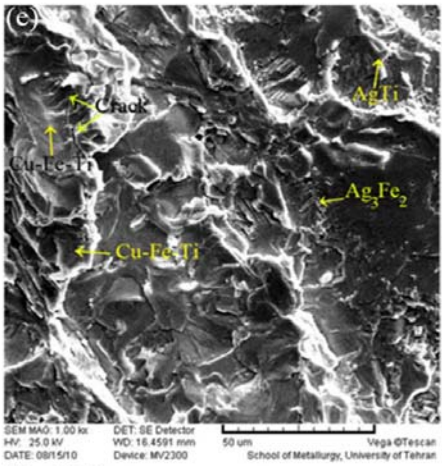


Fig.7. The fractography of the brazed joints prepared at a) 800 ºC, 5 min; b) 800 ºC, 15 min; c) 800 ºC, 30 min; d) 830 ºC, 30 min and e) 860 ºC, 30 min.

Fig.8 shows microhardness results of the brazed joint. Hardness value was ~~about~~ approximately similar to that of the AgCuZn braze alloy. The study showed that the magnitude of the hardness of the interface was between that of the base metals and braze alloy. As it was described earlier, according to SEM and XRD results, at both Ti-6Al-4V/AgCuZn and stainless steel 316L/AgCuZn interfaces, the reaction layers were produced. This might be the reason for increasing the hardness at the interface in comparison to that of the joint center [14].

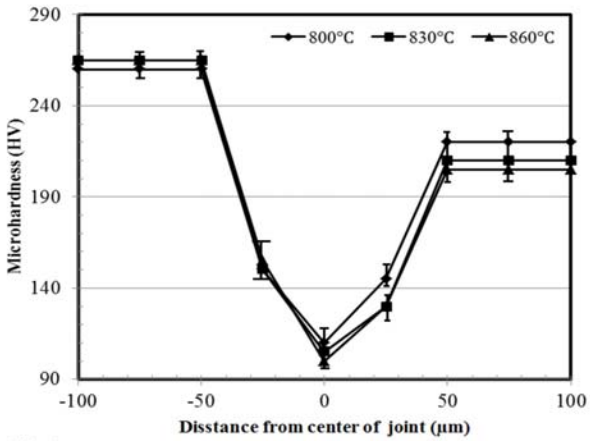


Fig.8. Microhardness results of the brazed joint prepared at different temperatures.

Conclusion

In the present study, the influence of the bonding temperature and time on the microstructure and mechanical properties of the dissimilar butt joints was investigated.

The effect of the intermetallic compounds formed at the interface of the joints were also studied with different characterization techniques. The main results are listed below:

1. The wettability of the AgCuZn braze alloy is improved by increasing the brazing temperature and time. Moreover, Ti-6Al-4V has shown better wettability compared to the stainless steel.
2. Microstructural observation showed that the existence of a soft phase such enriched with silver was helpful to produce a joint without any cracks.
3. By increasing the brazing temperature and time, the amount and variety of the intermetallic compounds was increased. These intermetallic compounds mainly consisted of CuTi and Fe-Cu-Ti. However, the TiAg intermetallic compound in the bonded area contributes to higher ductility of the joints.
4. Mechanical observation showed that the joint shear strength of the AgCuZn filler decreased with increasing the brazing temperature and time.

Acknowledgment

The authors express their gratitude to the school of metallurgy and materials engineering, University of Tehran, for providing the characterization equipments such as SEM and microhardness.

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