An Investigation on Metallurgical and Mechanical Properties of Vacuum Brazed Ti-6Al-4V to 316L Stainless Steel Using Zr-Based Filler Metal

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ABSTRACT

Both Ti-6Al-4V and 316L stainless steels are widely used as engineering alloys. Fusion welding of these two alloys is not easily possible due to their incomplete solubility in each other. Brazing is one of the best choices for joining dissimilar alloys. In this study, wettability experiments were done at 940and 970ºC for 5, 15 and 30 min. Also, joining of these two alloys was carried out at 940 and 970ºC for 15 min. Optical and scanning electron microscope (SEM) were used for metallurgical observations. Moreover, mechanical properties of the brazed joint were investigated using microhardness test. The results showed that some reaction layers were composed in the brazed joint's cross section. Ni-Ti intermetallic compounds were also observed in the brazed joint. Investigation of mechanical properties showed that hardness in the joint's center is higher than base metals.

Introduction

Both Ti-6Al-4V and 316L stainless steel are widely used as engineering alloys. Due to their mechanical properties such as corrosion resistance, they are widely used in industry. High strength to weight ratio, and excellent corrosion resistance of titanium and its alloys [1-4] have led to wide utilization of joining titanium and steel in aerospace, petrochemical industry, power generation, and transportation [1,5,6].

Welding of steel and titanium is hardly possible due to the low solubility of steel in α-Ti at room temperature. Fusion welding of titanium and steel makesbrittle and hard FeTi and Fe_2Ti intermetallic compounds and prevents a good technical weld to be achieved [7].

From the early 1950s, brazing of titanium alloys was developed to reduce the weight of spacecrafts. In order to improve the strength and corrosion resistance of titanium to titanium and titanium to stainless steel joints,

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over 100 filler metals have been produced and tested so far [8]. Brazing is one of the effective ways to make a strong joint between titanium and steel. This operation involves only the melting of filler metal, so it prevents the problems arising during the melting of dissimilar metals. To avoid unwanted impurities such as oxygen and nitrogen, titanium alloys must join in a neutral environment. Thus, titanium-steel joining is done in a vacuum furnace. In Ti-6Al-4V alloy, which is a α-β Ti alloy, phase transformation temperature of βto αis around 990°C, which reduces the mechanical properties of this alloy. Hence, it has been suggested that the brazing of Ti-6Al-4V alloy must be done at a temperature below 990°C. There are two fundamental problems in brazing of dissimilar metals. First, thermal residual stress is usually created due to the uneven thermal expansion of joining alloys. Second, brittle intermetallic compounds are formed after brazing in the interface between brazed alloy and substrate. Both of the above problems exist in brazing of Ti-6Al-4V and stainless steels [2,3]. It has been declared that pure silver, silver based alloys, zirconium based alloys, and copper based alloys are utilized for brazing of steel and titanium [3,6]. Low brazing temperature is preferred in most of the brazing processes. So, in this study, Stemet 1406 amorphous zirconium based filler metal has been used for brazing of titanium and stainless steel.

Experimental procedure

In this study, 316L Stainless steel were used with no heat treatment, and Ti-6Al-4V were used in annealed condition. Dimensions of the used 316L stainless steel and Ti-6Al-4V were 55×40×2 mm. These base metals were brazed together using Stemet 1406 zirconium based filler metal's foil (produced by Russia) in an amorphous form with 80 µm thickness. Lap joint was applied with 6mm overlapping. Chemical composition of base metals, filler metal and etching reagent used in this study is shown in **Tables 1**, **2**, and **3**, respectively.

Before testing, all samples were cleaned in an ultrasonic bath using acetone. An ADAMLE LHOMARGI resistant Vacuum furnace with the pressure of 5×10^{-4} Pa (Made by France) was used for joining base metals. Fixture was used in order to fix the position of the filler and base metals. It was designed according to the conditions of applied furnace as shown in **Fig. 1**.

Considering the wettability experiment results, joining of these two base metals was done at 940 and 970°C for 15min. Heating and cooling rate was set at 10°C/min in all experiments. Static sessile drop method was used in wettability experiment. 0.1±%1 gr from filler metal's foil was shaped as a quasi spherical and placed on the base metal.

Fig.1. Fixture used in this study.

Table 1. Base metals chemical composition.

(wt%)	Ti	Al	V	Fe	C	Mn	Cr	Mo	Ni
Ti-6Al-4V	Bal.	5.5	4.5	-	-	-	-	-	-
316L SS	-	-	-	Bal.	0.03	2.0	17.0	2.0	12.0

Table 2. Stemet 1406 brazed alloy composition.

(wt%)	Zr	Ti	Ni	Cu	Melting Range	Brazing Temperature
Stemet 1406	67	11	12	10	790-800°C	>900°C

Table 3. Chemical composition of etchants.

Used Condition	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 $CuCl_2$

After cooling in the furnace, each sample was sectioned for determining wetting angle, and optical microscope image of each sample's cross section was prepared. AutoCAD® software was used to determine the angle value. Optical microscope (model: OLYMPUS-TGH) and SEM (model: CamScan V2300) with 20kV accelerating voltage equipped with EDS chemical analysis were used for metallurgical investigations. XRD (model: STADIMP Germany) was applied for comparing phases of brazed joint with EDS results. Microhardnessmeasurement was used as an assessment of the mechanical properties. Vickers indenter and 200 gr load were applied for microhardness testing.

Results and Discussion

The base metals' wetting diagram with zirconium based filler metal is shown in **Fig. 2**. According to this diagram, it can be discerned that with increasing brazing time or temperature, wetting angle of both two base metals is reduced, and wetting is expected to be modified. At the temperature below 940°C, wetting of both base metals is almost the same, but at or above 940°C, wetting of Ti-6Al-4V base metal is likely to be better than 316L stainless steel base metal. At low temperatures, capillarity force cannot overcome the surface tension of molten droplet, preventing the molten droplet to flow on the base metal surface. It can be said that physical wetting cannot be a proper wetting. On the other hand, at low temperatures, the atomic diffusion coefficient is also low, so the chemical wetting cannotcause a proper wetting of base metals by the filler metal. With increasing temperature up to 940°C, both physical and chemical wettings are modified. This decreases the wetting angle. In cases where the brazing components are so reactive (as the alloys used in this study), chemical wetting is the dominant mechanism. In chemical wetting, more chemical reaction between the base and filler metals will improve the wetting and reduce the wetting angle. In chemical wetting, interface contains proper chemical bonds, and when the drop makes an obtuse angle (θ>90) with the solid surface, wetting will not be observed. It is completely reasonable due to the high contact

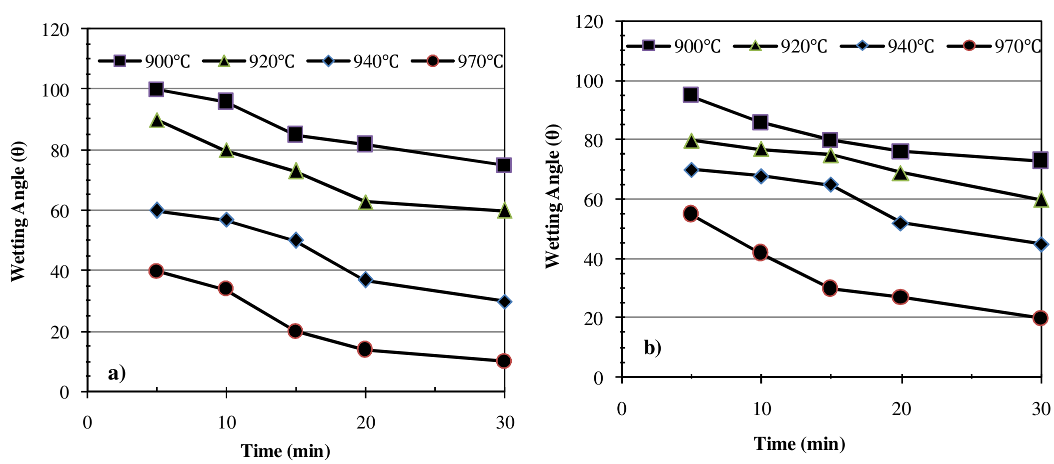


Fig. 2. Wetting of a) Ti-6Al-4V and b) 316L stainless steel base metals with Stemet 1406 filler metal.

angle. But, when the drop makes an acute angle with the solid surface, because of the reaction between this molten drop and solid surface, the reaction layer is formed exactly in the metal/metal interface. Naturally, the reaction layer creates a new interface. This new interface contains intermetallic compounds which are formed in the joint place, making a layer on the solid surface [9].

At temperatures below 940°C,wetting of base metals cannot be proper via Stemet 1406 filler metal, and due to the β transformation temperature in Ti-6Al-4V alloy, which is 990°C, if brazing temperature be higher than that, the annealing process will be needed again. So, 940 and 970°C were chosen as the brazing temperatures.

The optical microscope image of brazed joint is shown in **Fig. 3**. In both brazing conditions, reaction layers can be observed in both interfaces of base metal/filler metal. With increasing brazing temperature from 940 to 970°C, thickness of the reaction layers is not changed, but the type of phases should also be determined. Since with increasing the brazing temperature, the atomic diffusion is also increased, the type of phases in the brazed joint will be different. The presence of the reaction layers can be a good reason for the occurrence of chemical wetting in this study. SEM is needed for an accurate determination of interface phases.

The optical microscope image of brazed joint's cross section is shown in **Fig. 4**. EDS results show that with increasing the brazing temperature, continuity of the reaction layers is increased, and a larger amount of iron and nickel in the center of the brazed joint is visible. Whereas, the amount of titanium has been decreased in that point. This can be inferred by comparing the amount of titanium in F and C points. With increasing the brazing temperature, a larger amount of titanium is diffused from the center of the brazed joint to stainless steel. In both brazing conditions, there is a possibility of Ni-Ti based intermetallic compounds formation. With increasing the brazing temperature, the Ni/Ti ratio is increased in the brazed joint, but probably, the reaction layer of TiNi intermetallic compound is converted to $TiNi_3$ intermetallic compound.

To prevent the formation of Fe-Ti intermetallic compounds, fusion joining methods are not used in joining of titanium alloys and steels. These intermetallic compounds are so brittle and have a very low strength. It can be observed that 1406 Stemet zirconium based filler metal has prevented the diffusion of iron and titanium and the formation of the brittle Fe-Ti and Fe-Ti-Cu compounds.

In a research by Elrefaey, and Tillmann[6] on the brazing of pure titanium and low-carbonsteel with copper based filler metal in the temperature range of 970-1000°C for 15min, it is reported that the Fe-Cu-Ti, FeTi and Ti_2Cu intermetallic compounds have been

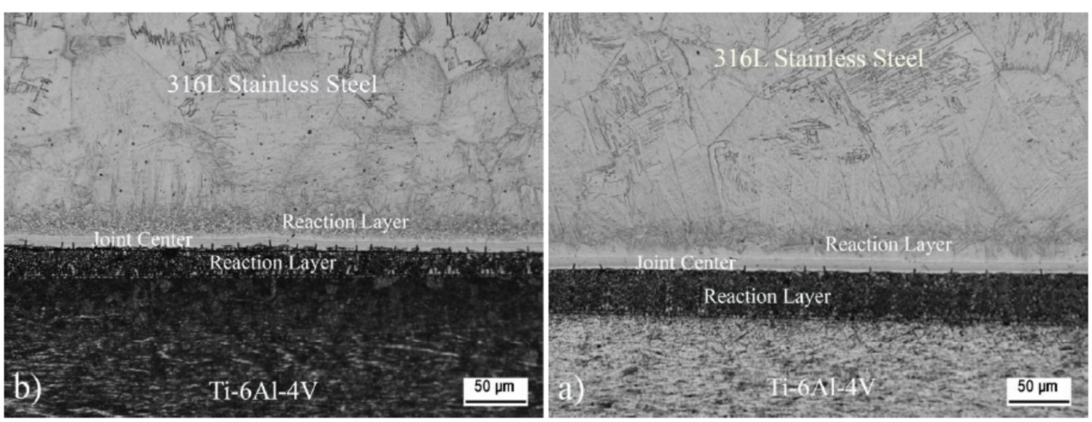
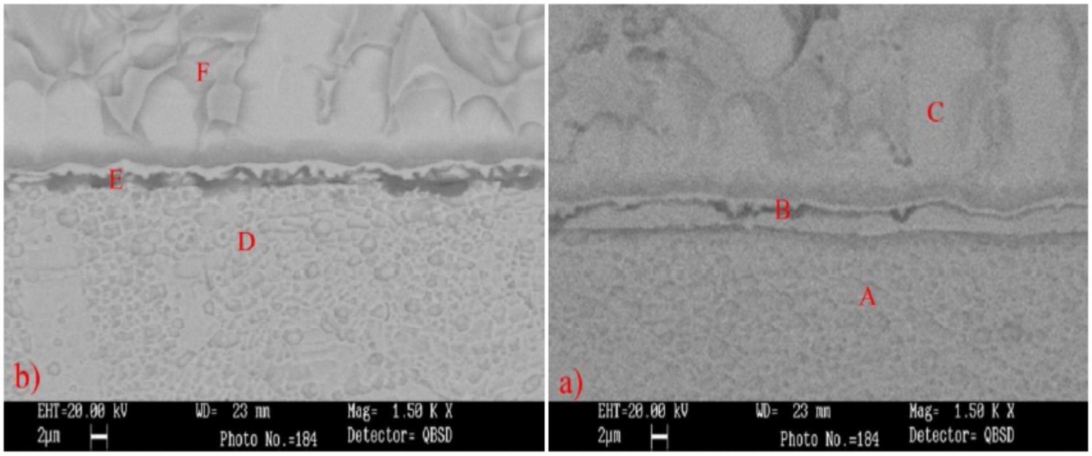


Fig.3. Optical microscope image of brazed joint.a) 940ºC, 15min. b) 970ºC, 15 min.



At%	Zr	Ti	Ni	Fe	Cu	Cr	Phase
A	18.22	40.25	8.18	19.49	6.91	6.95	-
B	20.25	5.77	5.34	52.97	-	15.67	TiNi
C	-	-	8.99	72.05	-	19.35	-
D	16.47	46.04	9.06	13.17	10.79	4.46	-
E	18.54	1.72	7.05	60.92	-	11.77	$TiNi_3$
F	-	5.22	8.93	71.46	-	19.60	-

Fig. 4. SEM-BSE image of brazed jointa) 940ºC, 15min b) 970ºC, 15 min.

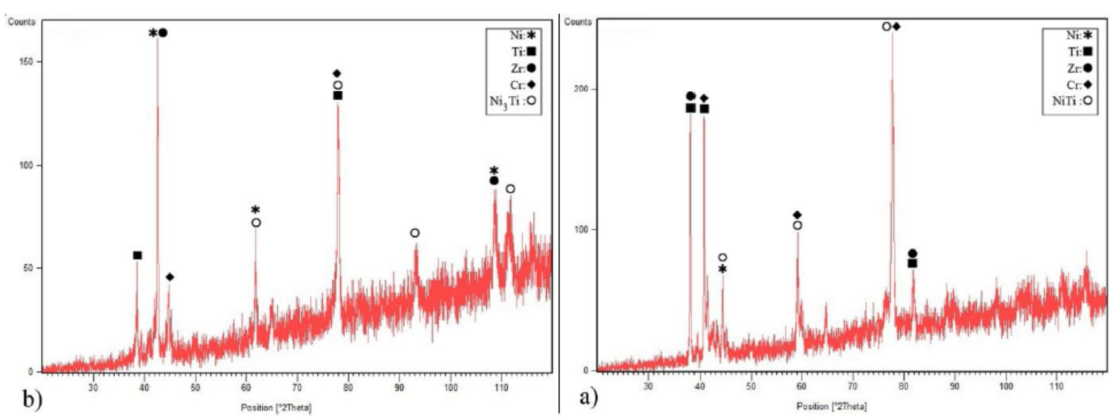


Fig. 5. XRD results of a) 940ºC, 15min b) 970ºC, 15 min.

observed. In another research, Liu et al. [1] have reported that in brazing of Ti-6Al-4V and 304L stainless steel with the silver based filler metal in the temperature range of 840-900°C, Fe-Ti-Cu intermetallic compounds can beobserved. Abdel et al. [4] reported that in a research on the brazing of pure titanium and low-carbon steel with the silver based filler metal, at temperatures above 750°C, TiCu intermetallic compounds canbe seen. According to the results of the present and previous researches which have used copper and silver based filler metals, it is specified that 1406 Stemet zirconium based filler metal can be a proper filler metal for joining of Ti-6Al-4V and 316L stainless steel and prevent the formation of detrimental intermetallic compounds such as Fe-Ti and Fe-Cu-Ti.

The XRD results are shown in **Fig. 5**. X-ray beam diameter is about 1mm, and the width of the brazed joint is about 100 µm. For a more accurate analysis of the joint's phases, XRD patterns from fracture surface of the shear test samples were taken.The results of EDS chemical analysis and XRD results are in agreement with each other.
The microhardness results of the samples are shown in **Fig. 6**. In order to extract the final results, microhardness test was done in three different areas of the samples and their average value was reported as the hardness number. Deviation of the acquired data is about ±4 HV. Hardness values show that there are some compounds with high hardness in the center of the brazed joint. On the other hand, in this reaction layer, the only possible intermetallic compound is based on Ni-Ti. Since the Ni-Ti based intermetallic compounds are not brittle and detrimental, and the their amount is very low in the center of the brazed joint, it can be said that zirconium based filler metal and the formation of solid solution between the existing elements of the joint are the most important reasons for the increased hardness in the center of the brazed joint. Hardness is in the interface of the center of the brazed joint and base metals.

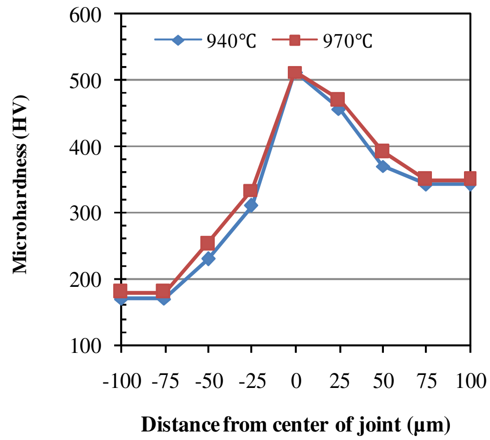


Fig. 6. Microhardness results of the brazed joint.

Conclusions

1- 1406 Stemet zirconium based filler metal has a good wettability on the Ti-6Al-4V base metals and 316L stainless steel. Wetting of the Ti-6Al-4V base metal is better than that of 316L stainless steel. With increasing the brazing temperature, wetting of both base metals is modified.
2- Metallurgical investigations showed that there are different reaction layers in the brazed joint. Ni-Ti based intermetallic compound is the only intermetallic compound in this joint which is not detrimental.
3- Microhardness test results showed that the highest hardness belongs to the center of thejoint, and the interfaces have the intermediate hardness value when compared to that of the joint's center and the base metal.
4- The metallurgical and mechanical properties of both brazing conditions are almost the same. Since the lower temperature is always preferred, 940°C can be a proper temperature for brazing of Ti-6Al-4V and 316L stainless steel using 1406 Stemet filler metal.

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