Effect of silver interlayer on transient liquid phase (TLP) bonding of Al 2024 to Ti-6Al-4V joints

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ABSTRACT

Transient liquid phase (TLP) bonding of two dissimilar alloys Al 2024 and Ti-6Al-4V was carried out at 580 and 600 °C for 45 min bonding time using a 30-μm-thick pure silver (Ag) foil interlayer. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) were used to investigate the phase structure and compositional changes across the joint region. Mechanical properties of the joints were investigated through shear strength and hardness tests. The joint formation was due to the solid-state diffusion of Ag and Cu into Al and Ti alloys, followed by eutectic formation, isothermal solidification, and formation of various intermetallic compounds such as Ag_2Al, Al_2Cu and Al_2CuMg along the Ag/Al2024 interface. Moreover, the interdiffusion of titanium and aluminum led to the formation of Al_3Ti intermetallic compounds. These types of intermetallics produced a metallurgical bond at Al 2024 interface. The study showed that the shear strength of the joint reaches a high value of 176.11 MPa obtained at the higher bonding temperature of 600 °C. It was also observed that the sample failed away from the base metal.

1-Introduction

Titanium (Ti) and aluminum (Al) alloys are being widely used in the industrial applications, such as aerospace, automobile and electronics industries, because of their light weight and unique performance features [1]. Therefore, joining Al to Ti alloys is particularly desirable for aerospace applications [2]. However, due to their notably different physical properties, Ti and Al alloys are hard to be bonded by the traditional fusion welding techniques [3].

Solid-state joining processes such as diffusion bonding (DB), transient liquid phase (TLP) bonding and brazing tend to be applicable for these alloys [4]. However, the uncontrollable formation of TiAl and $TiAl_3$ intermetallics, caused by direct contact of Al and Ti in the solid-state diffusion bonding, is the main problem. When an interlayer is placed between the two alloys, it was claimed that the formation of these intermetallic compounds becomes controllable [5]. Hence, the interlayer composition has an important role in the characteristics of the joint region [4].

Up to now, several studies have been done on the TLP bonding of Ti and Al alloys with different interlayers. For example, Alhazza et al. [6] joined Al 7075 to Ti-6Al-4V alloy by the TLP method using a 22-μm-thick Cu interlayer and reported the strength of 19.5 MPa after a bonding time of 30 min. They also used Sn-3.6Ag-1Cu interlayer and observed the highest

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bond strength of 42.3 MPa [3]. Moreover, Kenevisi et al. [1, 7] achieved the highest bond strength of 30 MPa and 36 MPa, respectively, in the TLP bonding of Al 7075 to Ti-6Al-4V using 50-µm-thick Sn-10Zn-3.5Bi and Sn-4Ag-3.5Bi interlayer films. Samavatian et al. [8] recorded the maximum bond strength of 35 MPa in the TLP bonding of Al 2024 to Ti-6Al-4V using an 80-µm-thick pure Sn interlayer foil. They also used a 50-µm-thick Cu-22Zn interlayer foil for the TLP bonding of Al 2024 to Ti-6Al-4V and reported the shear strength of 37 MPa after a bonding time of 60 min [5]. Chen et al. [9, 10] joined Ti-6Al-4V alloy to Al 1060 by ultrasonic-assisted brazing in air with a film of Al-12Si at 620 °C for which the bond strength was about 68 ± 2.3 MPa. Anbarzadeh et al. [11] acquired the welding tensile strength of 62 MPa in successive-stage TLP bonding of Al 2024 to Ti-6Al-4V using a 50-µm-thick Sn-5.3Ag-4.2Bi interlayer. Ag-based interlayers with high ductility and good metallurgical properties have been successfully used in welding similar and dissimilar high-melting-point metals, even ceramics [2].

The diffusion bonded Ti-Ti joints with silver interlayer was previously studied [12], but joining the titanium to aluminum by using the silver interlayers has not yet been reported. Hence, this method is likely to suggest different results in comparison with solid-state joining methods. In the present study, Ti-6Al-4V and Al 2024 alloys were successfully bonded using the diffusion bonding process at different bonding temperatures using a pure Ag foil interlayer. The effect of Ag interlayer on microstructure and mechanical properties of diffusion bonded Al-Ti joints was investigated.

2-Experimental procedure

The nominal chemical composition of the as-received materials is listed in Table 1. The specimens were cut into the dimension of 15×15×2 mm for metallographic investigations and 35×20×2 mm for shear strength tests (Fig. 1). The specimen surfaces were ground using 1200# emery paper, then were ultrasonically cleaned in an acetone bath to remove adhered contaminants, and dried in the air. The diffusion joining process was carried out under a constant bonding pressure of 1 MPa at the bonding temperatures of 580 and 600 °C for a bonding time of 45 min. Also, a 30-µm-thick pure (> 99.99 % wt.%) silver foil was used as the interlayer film. Vacuum pressure was less than 6×10^{-3} Pa. In the bonding process, the heating rate of the experiments was kept constant at 15 °C/min and the assemblies were cooled in the processing chamber under vacuum.

The etchant solution was composed of 10 ml HNO_3, 5 ml HF, and 85 ml distilled water, with etching time of 5 s. Microstructural characterizations were performed by the scanning electron microscopy (SEM), electron dispersive spectroscopy (EDS) and X-ray diffraction (XRD). The shear strength of the specimens was measured based on ASTM D1002-99 [13] at a cross-head speed of 1 mm/min. Finally, the microhardness measurements were conducted with a load of 50g.

3-Results and discussion

3-1-Microstructure and compositional changes

Figure 2 shows the microstructural changes in the diffusion zone of samples bonded at 580 and 600 °C with the holding time of 45 min. In both bonding temperatures, a eutectic-like phase can be observed along the Al 2024 grain boundaries. In the TLP process, the high-temperature of the chamber causes the diffusion of the alloying elements to form the molten eutectic. With the proceeding of the diffusion of the alloying elements, isothermal solidification occurs, and finally bonding is completed.

Table 1. Chemical composition of the base metals (in wt.%).

Alloys	Ti	Al	V	Cu	Mg	Mn	Fe	Si
Ti-6Al-4V	Bal.	5.80	4.14	0.02	-	<0.005	0.05	0.02
Al2024	0.03	Bal.	0.01	4.10	1.50	0.60	0.50	0.11

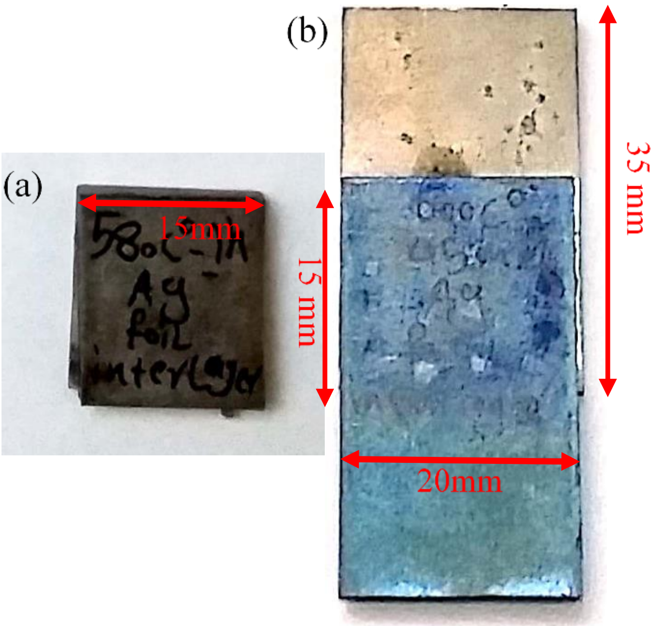

Fig. 1. Dimensions of base metals for (a) metallography and (b) shear strength test.

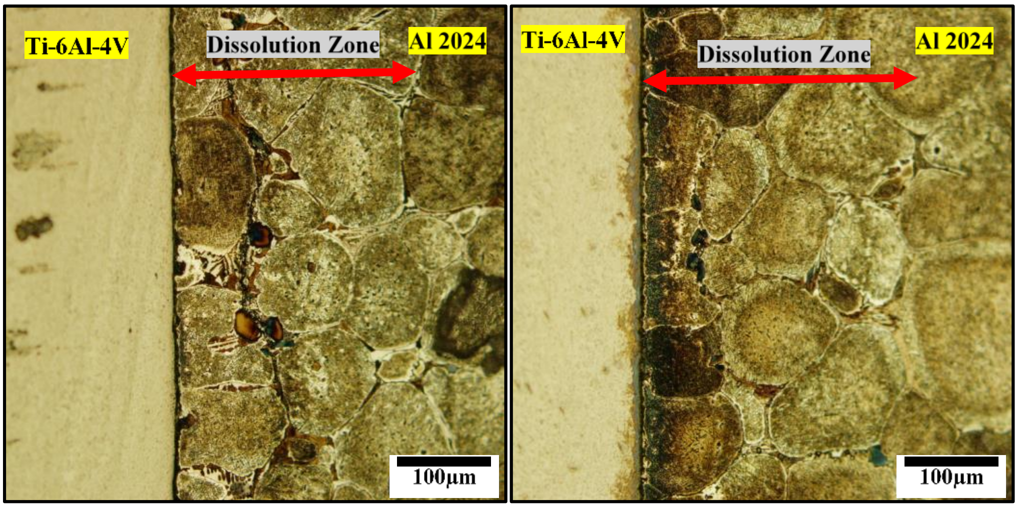

Fig. 2. OM micrographs of joint interface at bonding temperatures of (a) 580, (b) 600 °C.

The dissolution and widening zone in the TLP bonding is clearly observed in Fig. 2 for both bonding temperatures. Fig. 2 shows that the width of the dissolution zone is 260 and 300 µm for bonding temperatures of 580 and 600 °C, respectively, while that for Al/Ti joint using Cu-Zn interlayer is reported much lower [5]. This can be attributed to the formation of more eutectic phases below 600 °C when Ag interlayer is applied. In this condition, more liquid is created along the Al 2024 interface. Referring to Al-Ag binary phase diagram [14] and as observed by former researchers on the mechanisms of the diffusion of Ag into Al [2], it can be concluded that eutectic liquid formation due to the solid-state diffusion of Ag in base metals, is one of the initial bonding process stages at Al/Ag interface. As bonding time increases, Ag diffuses into Al and Ti, and the eutectic phase was formed along the Al 2024 grain boundaries. Subsequently, some intermetallics between Ti/Ag and Ti/Al can be developed.

For the preliminary characterization of the intergranular eutectic phase, the SEM micrographs from the bonded joints were studied. Fig. 3 exhibits the SEM micrograph of a bond made at 580 °C. The EDS analysis of selected regions in Fig. 3 is represented in Table 2. The diffusion of silver into the aluminum grain boundaries can be seen at points marked in Fig. 3. In the TLP process, mass transfer mainly depends on grain boundary diffusion which occurs much faster than the bulk diffusion. Region A is close to the Al 2024 interface and mainly consists of aluminum and silver with some concentrations of copper (4.35 wt.%), manganese (2.85 wt.%) and magnesium (2.85 wt.%). The inhomogeneity of the compositions suggests that the joint region contains various intermetallic phases. Points B and D designate the Ag-Al binary intermetallic (δ-Ag_2Al), indicative of the inter-diffusion of Ag and Al that occurs between the Ag foil and Al base metal. Regarding Fig. 3, area B encompasses areas B and D. According to the chemical analysis, although elements in these three areas are similar, the difference is raised by the amount of these elements. Ag, Cu and Mg contents in area B are 77.86 wt.%, 1.18 wt.%, 10.18 wt.%, respectively, while Cu content significantly goes up to 19.32 wt.% and Ag and Mg contents decrease in area C. This indicates that Cu is set back from area C to its environs and forms a distinct phase. Regions B and D are rich in silver. This reveals that silver could diffuse along the grain boundaries of Al alloy.

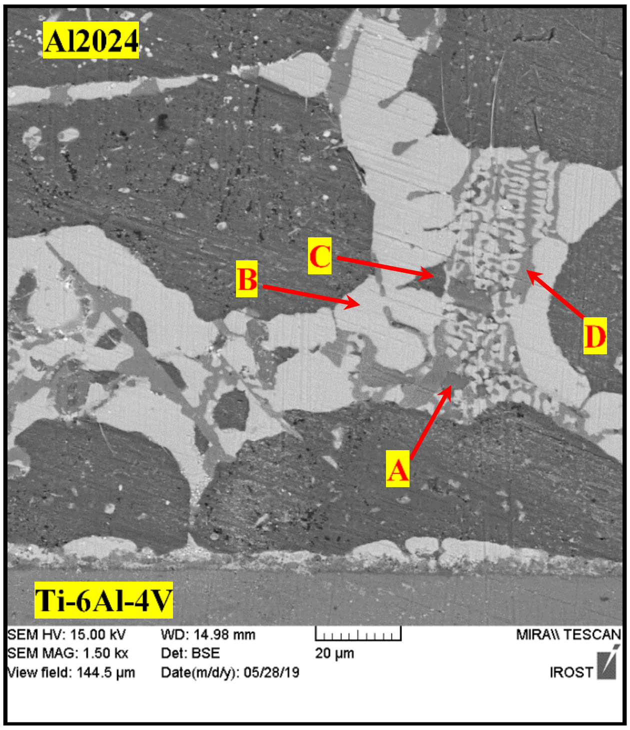

Fig. 3. SEM micrograph showing a joint made in 580 °C.

Table 2. EDS analysis (wt.%) of selected regions for bond made in 580 °C shown in Fig 3.

	Al	Ti	Ag	Cu	V	Mg	Mn
A	61.05	0.85	26.65	4.35	0.59	2.85	3.65
B	10.06	0.33	77.86	1.18	0.18	10.18	0.22
C	60.29	2.06	15.86	19.32	1.03	1.19	0.26
D	12.35	0.67	74.56	1.14	0.38	10.52	0.38

Fig. 4 shows the microstructure and elemental distributions of the joint formed at 600 °C for 45 min. The joint consists of a multilayered structure near the Al-Ti interface. The number of dots in each map indicates the presence of a certain element that is related to its concentration. The EDS maps for Ag and Cu show a considerable amount of silver and copper along the Al 2024 and Ti-6Al-4V interface. Considering the Cu and Al maps, it is concluded that the layered structure near the Al-Ti interface is rich in Al, Ag, and Cu which can be δ-Ag_2Al and θ (Al_2Cu). The Ag map shows complete diffusion of Ag into the parent metals. Thus, the diffusion mechanism is dominated at a rate somewhere between the diffusivity of liquid and solid in the joint zone. This phenomenon is called isothermal solidification. Based on the literature, the isothermal solidification process and widening of the bonding region can be divided into two steps: (a) forming of liquid/solid interface (liquid/solid diffusion) and (b) widening after completion of the isothermal solidification (solid-state diffusion). At first stages of the process, by diffusion of aluminum, silver, titanium, and copper from the base metal and the interlayer towards each other, the eutectic melt is formed, and the solid-liquid interface is created. The driving force for the isothermal solidification is the diffusion of melting point depressant (MPD) into the parent materials in the liquid/solid-state [4]. Either copper or silver will preferably diffuse as MPD into the Al 2024 alloy. Therefore, silver and copper will form eutectic phases with aluminum and its alloying elements (magnesium), and this will create a joint at the aluminum interface.

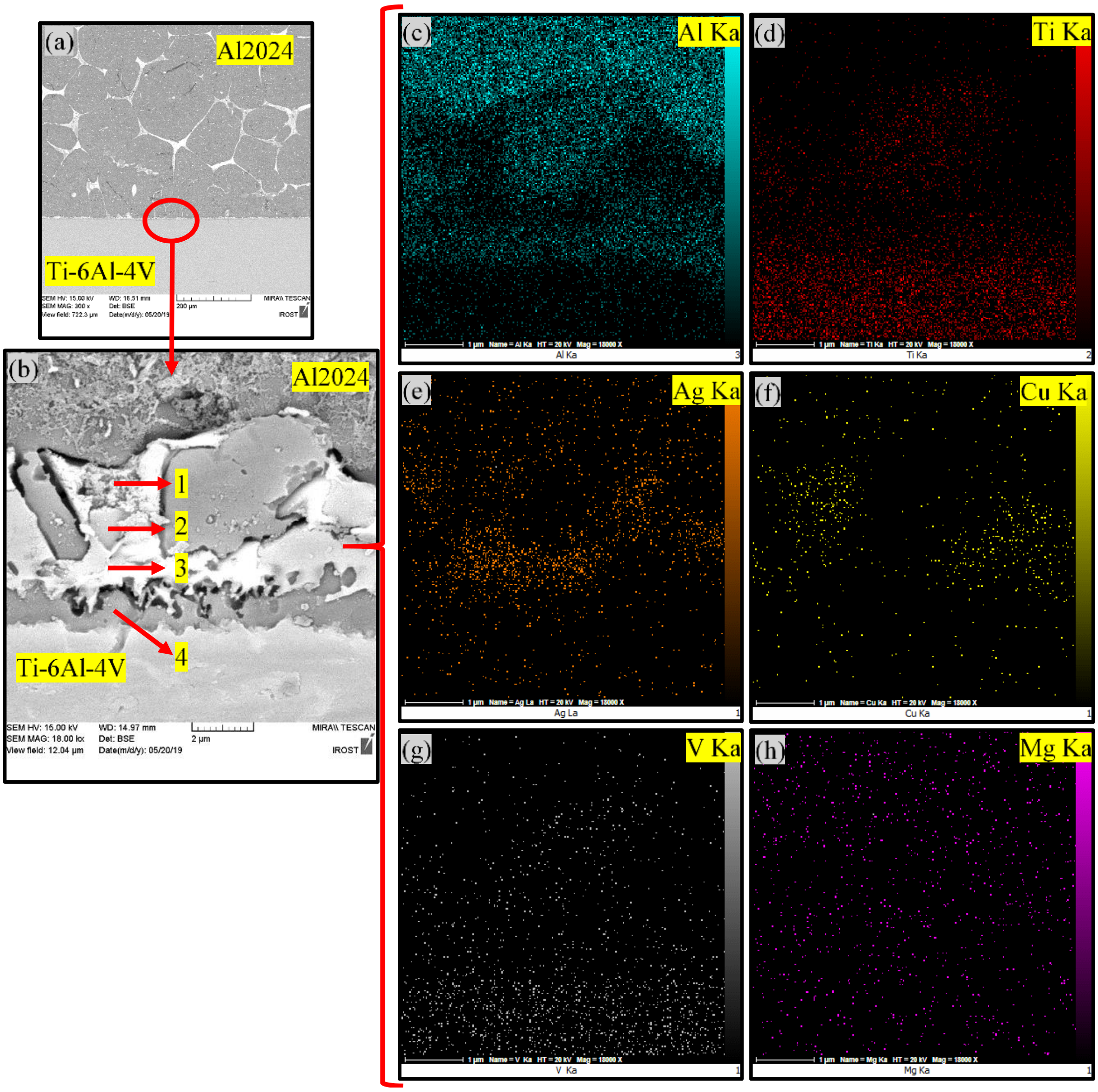

Fig. 4. EDS map for a bond made in 600 °C showing (a, b) joint region micrographs and concentration for (c) Al, (d) Ti, (e) Ag, (f) Cu, (g) V and (h) Mg.

Table 3. EDS analysis (wt.%) of selected regions for bond made in 600 °C shown in Fig 4.

	Al	Ti	Ag	Cu	V	Mg	Mn
1	40.81	3.50	6.25	45.78	0.83	2.62	0.21
2	40.01	12.76	28.80	16.73	0.34	1.13	0.24
3	26.55	7.45	57.90	5.02	0.18	2.71	0.19
4	52.58	30.89	10.73	3.59	0.91	0.92	0.38

Selected regions in a bond made at 600 °C for 45 min (Fig. 4) were analyzed using the EDS at regions marked as 1, 2, 3, 4 and the elemental compositions are shown in Table 3. Region 1 is located at the Al 2024 interface. Therefore, it can be considered to be responsible for the joint formation at the aluminum side. This region includes Al, Cu, and Mg elements. Considering the ternary phase diagram of these elements acquired by Styles et al. [15], the formation of θ-Al_2Cu and Al_2CuMg eutectic phases can be expected. Region 2 is rich in aluminum and has 28.80 wt.% of silver and 16.73 wt.% of copper and 12.76 wt.% of titanium. The inhomogeneity of the compositions suggests that the joint region contains various intermetallic phases. Region 3 is a silver-rich phase and contains 26.55 wt.% of aluminum and 7.45 wt.% of titanium which suggests that the interdiffusion between Al and Ti bases and Ag interlayer is active and sufficient for joint formation. Region 4 is located in the Ti–6Al–4V interface. Therefore, these regions could be responsible for joint formation at the titanium side. This region is rich in aluminum and titanium, and so it is most likely Al_3Ti intermetallic.

3-2-Identification of intermetallic compounds

The EDS results showed that the Al, Ti, Ag, Cu, V and Mg are present in the joint region of the bonds, indicating the probable formation of different intermetallics. In order to prove the formation of various intermetallic compounds in the joint zone, XRD analysis was employed. Fracture surfaces of a bond made at 600 °C for 45 min bonding time were analyzed by XRD and the results are shown in Fig. 5. According to the XRD results obtained from the Al side (Fig. 5a), there are several peaks caused by the formation of intermetallics coupled with the peaks for aluminum which have been recognized as Al, Ag_2Al, Al_2Cu, Al_3Ti and MgAg. Also, there are weak peak intensities of AlTi and Al_2CuMg. The results of the XRD analysis obtained from the Ti side are shown in Figure 5(b). The XRD pattern (Fig. 5b) shows that very weak peaks for Ag_2Al, Al_3Ti, and AlTi are detected on the surface of Ti side of the fractured specimen, signifying the low amount of these brittle intermetallic compounds in the joint zone. The presence of Ag interlayer between parent metals in the liquid state diffusion bonding process is the most important reason for the reduction in the formation of TiAl at the interface.

3-3-Mechanical characterization of joints

The mechanical properties of the joints were characterized by microhardness and tensile-shear tests.

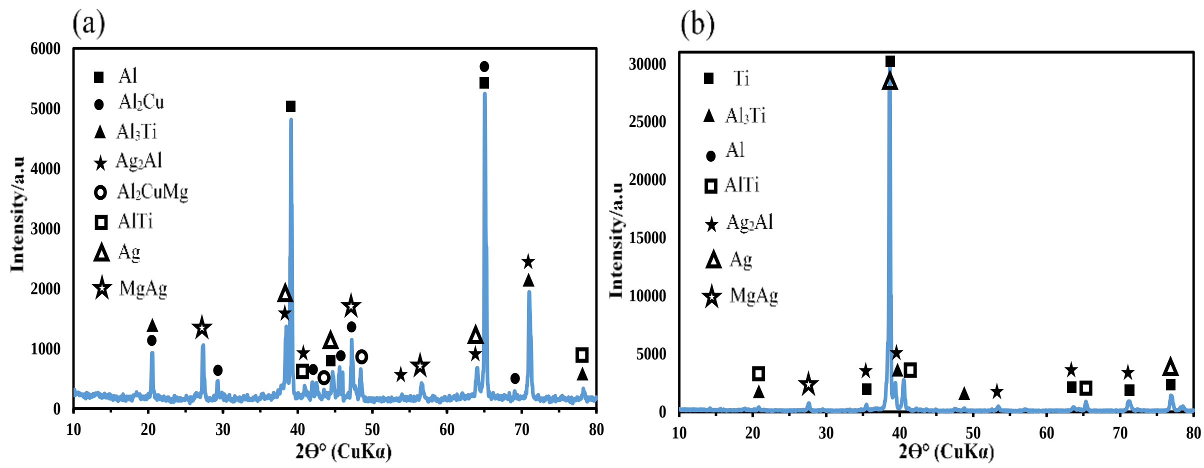

Fig. 5. XRD spectrum of a) fractured Al alloy surface and b) fractured Ti alloy surface.

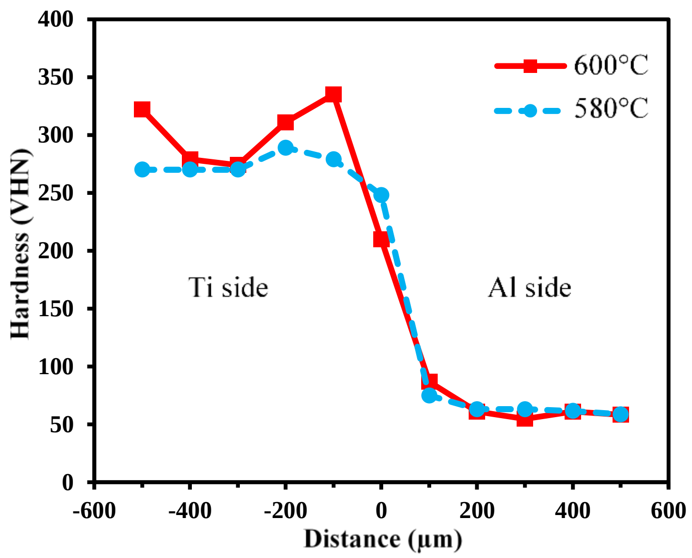

Fig. 6. Microhardness profiles across the joint region for bonds made in 580°C and 600 °C.

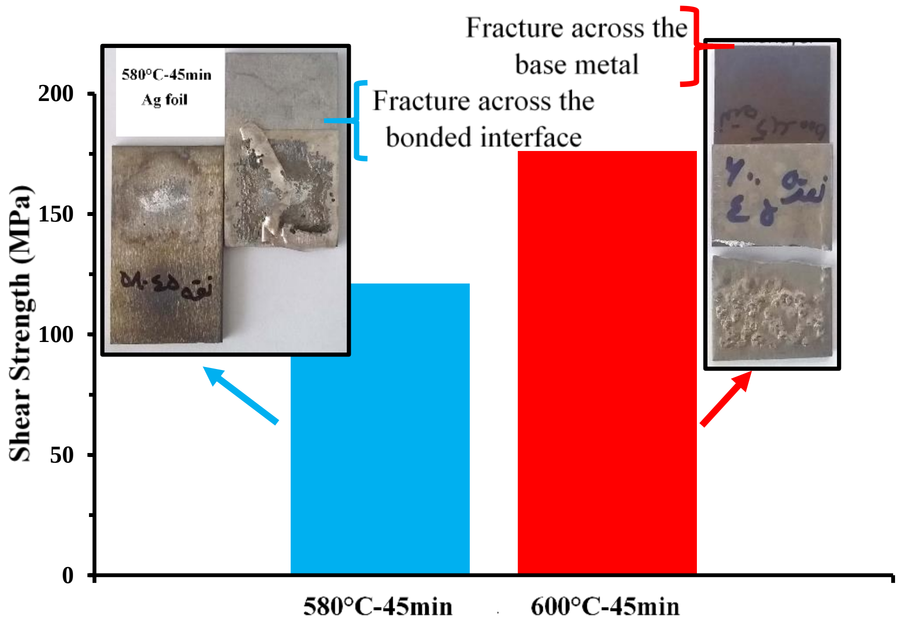

Fig. 7. Results of the shear strength and fracture zone of different joints.

Fig. 6 shows the results of the hardness test obtained from diffusion bonded joints made at different bonding temperatures. The general disposition of microhardness profiles shows that the hardness of the joint zone increases with an increase in bonding temperature. This can be an explanation for the formation of intermetallic compounds at the joint center. Moreover, the hardness value at Ti side of the interface for the bond made at 600 °C is noticeably higher than that for the bond made at 580 °C. Probably, the diffusion of Al and Ag into the titanium alloy and formation of intermetallics, such as Al_3Ti, cause this trend up at Ti side of the interface.

Shear strength of the diffusion bonds was determined by the single lap shear test. Illustration of the joint geometry prepared for performing the shear strength tests is shown in Fig. 1. The room temperature shear strength of the diffusion bonded joints with the change in bonding temperature is shown in Fig. 7. The results showed that the strength of the bonds notably depends on the bonding temperature and the interface microstructure. The maximum shear strength of 176.11 MPa was obtained at a higher bonding temperature of 600 °C. This sample failed away from the base metal, as seen in Fig. 7. The maximum shear strength recorded in the present study is higher than those obtained in all previous works with different compositions of foil and welding variables [1, 3, 5-11]. At the lower bonding temperature, i.e. 580 °C, the extent of the diffusion for the alloying elements at the interlayer zone is limited. Therefore, due to the remaining interlayer exists in the interface (Fig. 7), the bond strength value decreased to 121.13 MPa. In this sample, failure occurred across the bonded interface close to the Ti alloy (Fig. 7). This indicates that solid-state diffusion bonding at the Ti alloy side is weaker than the TLP bonded part of the joint at Al alloy side. Nevertheless, the shear strength of 121.13 MPa is obtained at 580 °C. This value is also higher than those obtained in all previous works. As bonding temperature increases, the diffusion of the elements resulted in the formation of compounds that produce metallurgical bonds at the joint interface.

4-Conclusion

The TLP bonding of Al 2024 alloy to Ti-6Al-4V alloy was successfully carried out at 580 and 600 °C for 45 min bonding time, using a 30-μm-thick pure silver foil interlayer. The main obtained results are as follow:

1. Diffusion of silver and copper into Al 2024 alloy resulted in the formation of eutectic phases and various intermetallic compounds, namely Ag_2Al, Al_2Cu and Al_2CuMg. These types of intermetallics produced a metallurgical bond at the Al2024 interface.
2. Diffusion of Ag and Cu in Al and Ti resulted in the formation of several intermetallics which produced metallurgical bond at the interface. Also, the interdiffusion of titanium and aluminum led to the formation of Al_3Ti intermetallic compounds.
3. The joint strength depends on the metallurgical structure of the diffusion zone. The shear strength of the joint reaches the high value of 176.11 MPa obtained at a higher bonding temperature of 600 °C. The sample failed away from the base metal. The maximum shear strength recorded in the present study is higher than those obtained in all previous works where different compositions of foil and welding variables were used.

The authors declare that they have no conflict of interest.

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