DIFFUSION BONDING AND TRANSIENT LIQUID PHASE JOINING OF TITANIUM TO AISi 304 STAINLESS STEEL WITH AN ALUMINUM INTERLAYER

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Abstract

Titanium and AISI 304 stainless steel were joined using a 0.1 mm thick aluminum foil interlayer at temperatures of 550, 650 and 700 °C for 1 h under 2 MPa pressure in vacuum. The interface microstructures of the bonded samples were observed using the optical and scanning electron microscopes. The chemical analysis was performed with energy dispersion spectroscopy. The effect of bonding temperature on joints microstructure, composition and microhardness was investigated. $FeAl_3$ and Fe_2Al_5 intermetallic layers were observed at the stainless steel/aluminum interfaces. At the aluminum/titanium interfaces TiAl, $TiAl_2$ and $TiAl_3$ intermetallic layers were identified. The width of intermetallic layers for both interfaces increased gradually with the increase in bonding temperature. The irregular shaped particles of Al_7Cr were additionally observed in aluminum matrix for joints that were transient-liquid-phase bonded at 700 °C. Microhardness of joints achieved values from 220 to 870 HV and was higher than that one for base metals. The microhardness values for analogous intermetallic layers increased with increasing temperature of bonding.

Keywords: Titanium, stainless steel, aluminum, diffusion bonding, TLP joining, microstructure

1. INTRODUCTION

Titanium is a metal with very high specific strength and good corrosion and erosion resistance. The three useful properties have led to a considerable interest in joining titanium and its alloys to stainless steel for many industrial applications [1-3]. Unfortunately, titanium and corrosion-resistant chromium-nickel stainless steels belong to structural materials which are quite difficult to join, which is mainly caused by the presence of stable TiO_2 and $FeO{\cdot}Cr_2O_3$ oxides on their surfaces [4]. Due to the low solubility of iron in alpha titanium at room temperature welding of titanium and stainless steel is very difficult. When the two materials are joined by conventional fusion [5] or friction welding [6] it results in formation of brittle and hard intermetallic phases near the interface. In order to braze titanium to stainless steel many different filler metals can be used including pure silver, silver base alloys, titanium base alloys and copper base alloys [7]. Regrettably, titanium, being a reactive metal, reacts easily with liquid filler materials and forms intermetallic phases. Usually they are located as continuous layers on braze boundaries [8]. Very practical method of joining different materials is diffusion bonding that produces solid-state coalescence through the application of pressure at a temperature below the melting point of the joined materials [9, 10]. Unfortunately, joints produced by direct diffusion bonding between titanium and stainless steel show the formation of brittle FeTi, Fe_2Ti, Fe_2Ti_4O and Cr_2Ti phases in the diffusion interface [3]. Hence, the only way to attain strong joints of titanium to stainless steel appears to be diffusion bonding with an appropriate filler metal. Copper, nickel, silver and their alloys were used previously as intermediate materials [11-14]. It is also possible and advantageous to use aluminum as a filler metal because it has a low price and its melting point is much lower with respect to other metals. As reported He et al. [15] titanium and stainless steel can be successfully diffusion bonded using an aluminum alloy interlayer in the temperature range from 350 to 600 °C. Transient liquid phase (TLP) bonding combines the merits of diffusion bonding and liquid phase joining processes and it is an attractive alternative for joining and repair of similar and dissimilar materials [16]. The TLP bonding involves sandwiching a filler metal between the substrate materials, and subjecting them to a high temperature. The temperature must be higher than the liquidus temperature of the filler and lower than the solidus temperatures of the bonded materials. At the bonding temperature the interlayer metal melts and rapidly attains equilibrium with the solid materials through the process of melt-back dissolution of the substrates. As a consequence of interdiffusion of alloying elements between the base materials and the liquid, the melting point of the interlayer liquid at the liquid-solid interface increases resulting in isothermal solidification. If sufficient time for complete solidification is not allowed it can lead to formation of eutectic mixtures occurring along the joint centerline that may be hurtful for joint's properties. This paper aims to study the influence of the diffusion bonding and TLP joining parameters on the microstructure and microhardness of titanium and stainless steel joints produced with the use of aluminum as an interlayer.

2. EXPERIMENTAL PROCEDURE

2.1. Specimen preparation

Cylindrical Grade 2 titanium and AISI 304 stainless steel rods both having 8 mm diameter were cut into 10 mm long specimens. Chemical compositions and room-temperature mechanical properties of base materials are given in **Table 1**.

Table 1 Chemical compositions and mechanical properties of the base materials (accordingly to certificates)

Materials	Chemical elements (wt. %)											
	Fe	Ti	C	Cr	Ni	Mn	Si	O	Mo	N	H	P + S
Titanium	0.171	bal.	0.024	-	-	-	-	0.142	-	0.008	0.001	-
AISI 304	bal.	-	0.025	18.15	8.05	1.46	0.39	-	0.38	0.063	-	0.05
	Yield strength (MPa)				UTS (MPa)				Elongation (%)			
Titanium	350				420				38			
AISI 304	480				945				26			

The joining surfaces of the specimens were ground using several stages up to 1200 grit. The 0.1 mm thick aluminum foil was used as an intermediate metal that after polishing was cut into circular profiles having 8 mm diameter. Since it was necessary to remove oxide layers, the titanium cylinders and aluminum foils were etched in an aqueous 2 % solution of hydrofluoric acid, while the stainless steel specimens in an aqueous 5% solution of nitric acid. All specimens were then cleaned in water and dried rapidly in air. A steel clamp was used to keep in contact the joined titanium and stainless steel cylinders with the inserted aluminum interlayer. The fixture was placed into a specially constructed vacuum furnace equipped with a piston that could move. Therefore it was possible to apply the compressive stress of 2 MPa along the longitudinal direction in order to obtain good initial contact between joined metals. The bonding was carried out at 550, 600, 650 and 700 °C for 1 h in 10^{-3} Pa vacuum. After the joining operation samples were furnace-cooled.

2.2. Microstructural characterization and microhardness measurements

For characterization, the specimens were cut, mounted in a cold setting resin and mechanically prepared initially with successively finer silicon carbide papers up to 1200 grit and finally using 1 μm diamond suspension and Struers polishing machine. Microstructural observations were performed using a JEOL JMS-5400 scanning electron microscope (SEM) and a Nikon ECLIPSE MA200 optical microscope. Before the samples were examined with the optical microscope they had been etched. The titanium side and the joint were etched in an aqueous 5% solution of hydrofluoric acid. The samples for SEM investigations were not etched. The chemical analysis was performed using an Oxford Instruments ISIS-300 energy dispersive X-ray spectrometer (EDS). Composition of the phases was determined by comparison of the results of the microprobe analysis with the data in the ternary Al-Fe-Ti phase diagram [17].The microhardness along the cross-section of the diffusion bonded joints was performed by a Matsuzawa MMT microhardness tester under load of 0.981 N with a testing time of 15 s.

3. RESULTS AND DISCUSSION

3.1. Effect of bonding temperature on joint microstructure and composition

In order to study the effect of bonding temperature on joints microstructure, samples were bonded at 550, 600, 650 and 700 °C for 1 h. Microstructural examinations showed that titanium and stainless steel were joined through the formation of interface layers between stainless steel/aluminum on one side and aluminum/titanium on the other side as a result of the diffusion of metallic elements. The structure of the joints differed significantly with increasing of the bonding temperature. The example cross-sections of the joints performed for all the temperatures are presented in **Fig. 1**. To characterize the reaction areas of the joints, SEM study was also carried out on the reaction layers, as it is shown in **Fig. 2**. Moreover, the composition of the chemical species was determined near steel/aluminum and aluminum/titanium interfaces for all obtained joints. At the stainless steel/aluminum interface the bright shaded layer neighboring to steel has been observed which has a composition of 72.91 at.% Al and 20.51 at.% Fe with small amounts of Cr (4.96 at.%) and Ni (0.98 at.%) (**Fig. 3**). Under the first layer, second layer neighboring to aluminum has been identified. It has a composition of 74.86 at.% Al and 17.47 at.% Fe with small amounts of Cr and Ni.

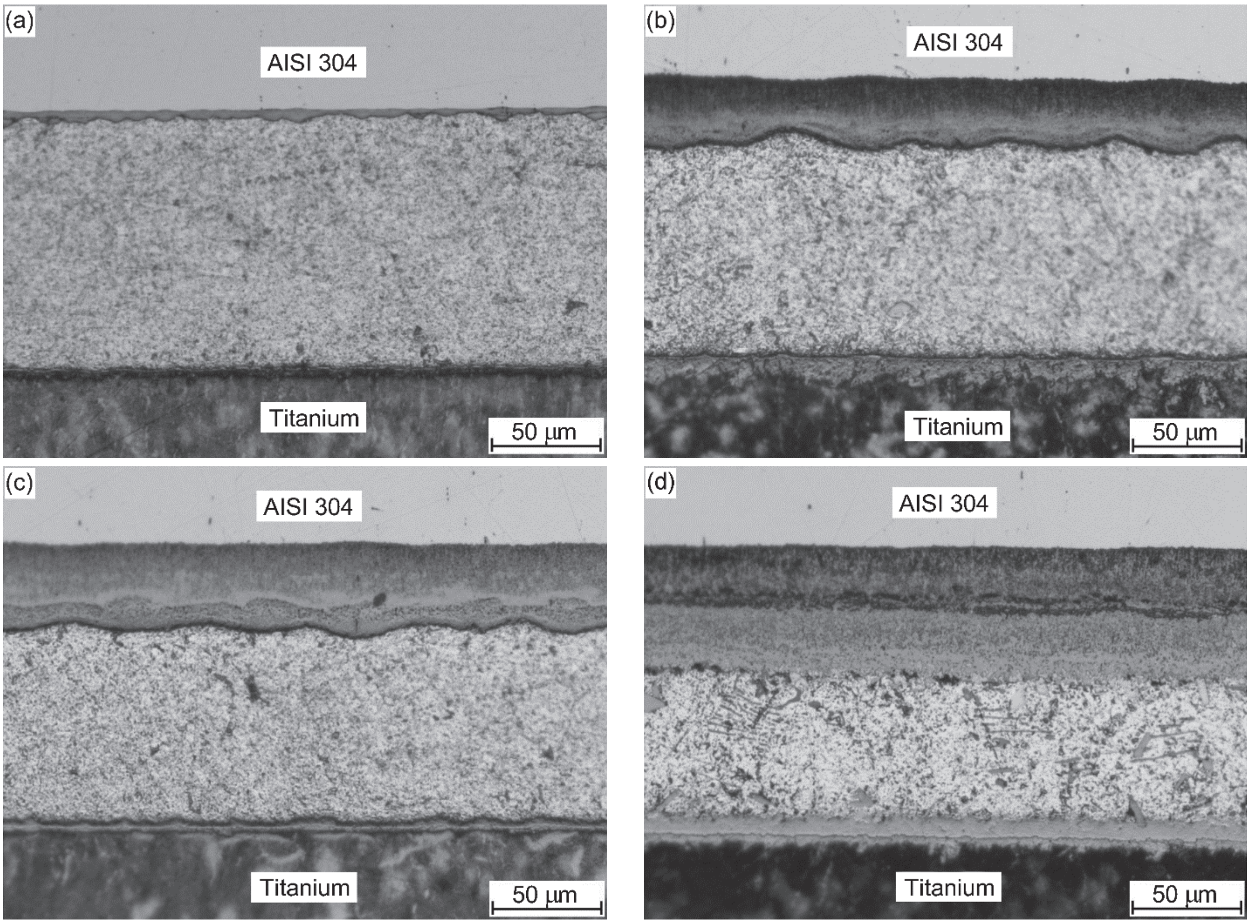

Fig. 1 Microstructure of the joints performed at 550 °C (a), 600 °C (b), 650 °C (c) and 700 °C (d) for 1 h

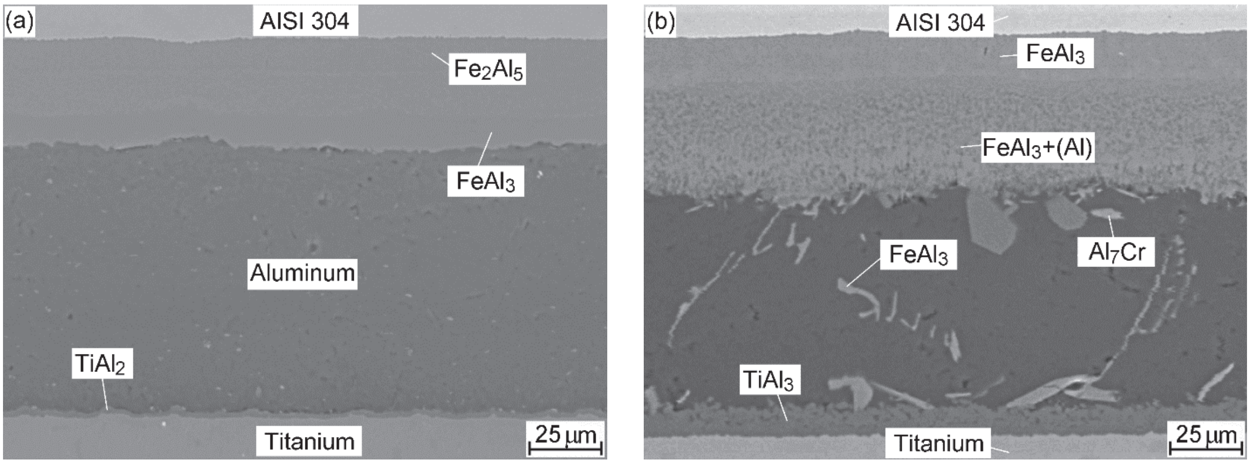

Fig. 2 SEM micrographs of the bonded joints processed at 650 °C (a) and 700 °C (b)

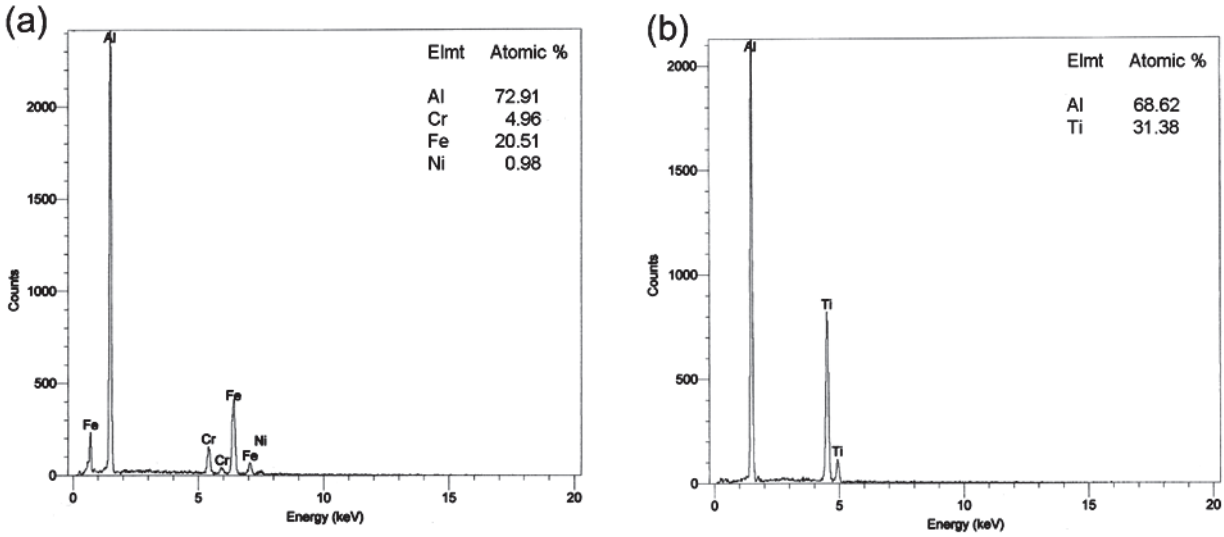

Fig. 3 X-ray spectra for Fe_2Al_5 (a) and $TiAl_2$ (b) intermetallic phases

According to the chemical analyses and the Al-Fe-Ti ternary phase diagram, it can be assumed that the phases present in the form of layers at the stainless steel/aluminum interface are Fe_2Al_5 and $FeAl_3$ with an amount of Cr and Ni admixtures. It is worth noting that the Fe_2Al_5 phase was formed mainly in the joints bonded at temperatures lower than 650 °C. The irregular shaped particles of $FeAl_3$ and additionally Al_7Cr containing 86.61 at.% Al and 8.72 at.% Cr with amounts of Ti (1.69 at.%) and Fe (2.62 at.%) have been additionally observed in aluminum matrix for joints that were transient-liquid-phase bonded at 700 °C (**Fig. 2b**). At the aluminum/titanium interface, the thin layer of $TiAl_2$ containing 68.62 at.% Al and 31.38 at.% Ti have been observed especially when the joining temperature was lower than 650 °C. The layer of regular particles containing 74.83 at.% Al and 25.17 at.% Ti has been found at the aluminum/titanium interface when bonding temperature was 700 °C (**Figs. 2b** and **4**). The particles are the $TiAl_3$ intermetallic phase. The region contains also small amount of TiAl.

The width of intermetallic layers for stainless steel/aluminum and aluminum/titanium interfaces increases gradually with the increase in bonding temperature. Measurement shown that the total width of intermetallic layers formed at the stainless steel/aluminum interface at 700 °C is about 20 times larger than that one for samples processed at 550 °C and about 14 times larger than that one for samples bonded at 650 °C.

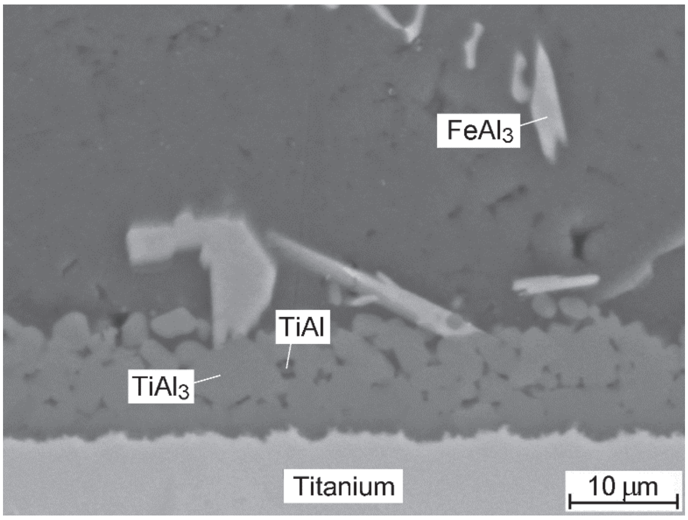

Fig. 4 SEM image of the aluminum/titanium interface for the joint processed at 700 °C

3.2. Effect of bonding temperature on microhardness of bonded joints

The maximum microhardness values in the range from 506 to 870 HV were achieved at the stainless steel/aluminum interface due to the presence of the Fe_2Al_5 and $FeAl_3$ intermetallic phases. Microhardness of joints at the aluminum/titanium interface achieved value of 220 HV. In the middle of the joints microhardness values ranged from 28 to 44 HV. An increase in the bonding temperature resulted in a considerably increasing microhardness of the joints due to the formation of hard Fe-Al, Al-Cr and Ti-Al based intermetallic phases. The microhardness values for analogous intermetallic layers also increased with increasing temperature of bonding because of diffusion of Fe, Cr and Ni to intermetallics.

4. CONCLUSIONS

Bonding of titanium to AISI 304 stainless steel using aluminum foil as an interlayer can be properly accomplished in the temperature range from 550 to 700 °C resulting in joints with good quality. The microstructure of the joints and thickness of reaction products change significantly with increasing in the processing temperature. $FeAl_3$ and Fe_2Al_5 intermetallic layers with an amount of Cr and Ni admixtures are formed at the stainless steel-aluminum interfaces. Nevertheless, only $FeAl_3$ intermetallic phase can be observed at the stainless steel/aluminum interface when the bonding temperature is higher than 650 °C. The irregular shaped particles of Al_7Cr are additionally formed in aluminum matrix for joints that are transient-liquid-phase bonded at 700 °C. When the bonding temperature is lower than 650 °C, TiAl, $TiAl_2$ and $TiAl_3$ intermetallic layers occur at the aluminum/titanium interfaces. After transient-liquid-phase bonding at 700 °C only $TiAl_3$ occurs at the aluminum/titanium interface. Microhardness in the joints reaches higher value than for titanium and stainless steel. The values of microhardness for analogous intermetallic layers increase with the increase in bonding temperature due to diffusion of admixtures to intermetallic phases.

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