INFLUENCE OF BONDING PRESSURE ON THE DISSIMILAR JOINTS OF TITANIUM AND STAINLESS STEEL WITH AN ALUMINUM INTERLAYER

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Abstract

In present investigation diffusion bonded joints between titanium (Grade 2) and stainless steel (X5CrNi18-10) using 120 µm thick aluminum foil as a filler metal were produced at 600 °C for 60 minutes under: 2, 4, 6 and 8 MPa pressure in vacuum. The microstructure was investigated using light optical microscopy and scanning electron microscopy equipped with an energy dispersive X-ray system (EDS) to determine chemical composition of the joint. Joinings between dissimilar materials result in formation of intermetallic phases in the interface. The $FeAl_3$ and Fe_2Al_5 intermetallic layers were observed at the stainless steel-aluminum interfaces. At the aluminum-titanium interfaces $TiAl_2$ intermetallic layers were identified. The investigation shows that the pressure is important factor to control mechanical properties of diffusion bonded joints. The highest shear strength (88 MPa) was achieved for samples prepared using the highest pressure value, and for those samples were performed corrosion resistance test in 3 % sodium chloride solution. The samples were kept in the solution for 24, 48, 72 and 96 h. Corrosion resistance of the diffusion brazed joints was evaluated by the weight loss during the test.

Keywords: Diffusion bonding, titanium, stainless steel, aluminum, interlayer

1. INTRODUCTION

In recent years, considerable interest has been given to titanium and its alloys because of its unique properties such as high strength, toughness, erosion resistance and low thermal conductivity and density [1, 2]. Nuclear, chemical, aerospace and space industries strongly demand dissimilar joints of titanium and titanium alloys to austenitic stainless steel due to good corrosion resistance and satisfactory mechanical behavior [3, 4]. This type of joints finds implementations in satellite cooling system, in the reprocessing plant at Kalpakkam in electrolytic dissolver unit, as well as in subassemblies of nuclear reactors and aircraft engines [5-7]. Traditional fusion welding of dissimilar materials results in different problems like distortion of components, formation of stress concentration sites, development of chemical heterogeneities and a number of intermetallic phases that are formed in the weld pool. In addition, titanium and its alloys are chemically reactive, they are very difficult to weld, because they can easily pick up nitrogen and oxygen from the atmosphere [8, 9]. Hence, solid state diffusion bonding process is recommended for materials with extremely different physical and mechanical properties [10]. Existing literature reports that direct bonding between titanium and stainless steel results in formation of numerous intermetallic phases due to the limited solubility of iron in titanium and these intermetallics deteriorate the bond strength. In addition, high internal stresses are formed because of a large difference of linear expansion and heat transmission coefficient between titanium and stainless steel which lead to a bonding crack, so indirect bonding by adding interlayer metal is now largely used [11-13]. The use of appropriate intermediate materials can also inhibit diffusion of undesired elements. Konieczny et al. [14, 15] have reported that the copper layer of 0.1 mm thickness effectively blocks the diffusion of titanium to stainless steel up to 900 °C if the bonding time is no longer than 30 minutes. Nickel, silver and their alloys were also used as intermediate materials [16, 17]. In this respect aluminum can be considered as a useful interlayer due to the lowering of bonding parameters for solid state diffusion bonding and aluminum has certain erosion resistance and excellent plasticity [18, 19]. Diffusion bonding depends on three major parameters like bonding temperature, holding time and bonding pressure. Previous attempt [20] shows the influence of bonding temperature on the titanium stainless steel joints with aluminum interlayer. The present investigation reports the influence of the bonding pressure on the microstructure, shear strength and corrosion resistance of diffusion bonded joints of titanium and stainless steel with aluminum as an intermediate material.

2. EXPERIMENTAL PROCEDURE

The base materials used for the dissimilar joints were commercially pure titanium (Grade 2) and stainless steel (X5CrNi18-10), both received in the form of cylindrical rods having 8 mm diameter and 2000 mm length, and aluminum foil of 120 µm thickness. The nominal chemical composition of these materials at room temperature is given in **Table 1**.

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

Material	Titanium (Grade 2)	Stainless steel (X5CrNi 18-10)	Aluminum (Al 99.5)
Chemical composition (wt. %)	Ti: 99.654; Fe: 0.171; C: 0.024; N: 0.008; O: 0.142; H: 0.001	Fe: 71.495; C: 0.025; Mn: 1.460 Si: 0.39; P: 0.038; S: 0.012; Cr: 18.15; Ni: 8.05; Mo: 0.38	Al: 99.53; Fe: 0.21; Si: 0.16; Zn: 0.05; Cu: 0.03; Ti: 0.02

Cylindrical specimens of 8 mm diameter and 10 mm length were machined from the titanium and stainless steel rods. The circular profile discs with 8 mm diameter were excised from the aluminum foil. The faces of the cylinders were prepared by conventional grinding and polishing techniques and final polishing was made with 0.5 µm alumina suspension. To remove oxide layers from the base materials, the samples were etched in solutions: titanium and aluminum in an aqueous 5 % solution of HF, stainless steel in an aqueous 10 % solution of HCl. All specimens were then cleaned in water and dried rapidly in air. The mating surfaces of the samples were kept in contact with steel clamp and inserted in a vacuum chamber. The bonding pressure in a range from 2 to 8 MPa along the longitudinal direction was applied at room temperature. Diffusion brazing was carried out in a vacuum furnace Czylok PRC 77/1150 at the temperature of 600 °C for 60 minutes with a vacuum of 10^{-3} Pa. The samples were cooled with the furnace. The specimens for metallographic examination were cut out longitudinally and their surfaces were prepared by conventional techniques, using sandpapers of 180 to 1200 grit, alumina suspension with a grain size of 0.5 µm and colloidal silica with a grain size of 0.05 µm. The titanium side and the joint were etched in an aqueous solution of 95 ml H_2O and 5 ml HF. The samples were observed in a light microscope Nikon Eclipse MA200 to reveal the structural changes due to diffusion. The polished surfaces of the brazed couples were also examined in a scanning electron microscope (SEM) JEOL JMS-5400 to obtain finer structural details in the diffusion zone. The composition of the reaction layers was determined in atomic percent using Oxford Instruments ISIS energy dispersive X-ray spectrometer (EDS) attached to the SEM. The results of the EDS analysis were compared with the binary phase diagrams of basic components. The shear strength of the brazed joints was evaluated at room temperature using a LabTest 5.20SP1 testing machine at a crosshead speed of 10 mm/min. Five samples were tested for each processing parameter. The corrosion resistance test was performed in 3 % sodium chloride solution. The samples were kept in the solution for 24, 48, 72 and 96 h. Corrosion resistance of the diffusion brazed joints was evaluated by the weight loss during the test using analytical balance Radwag AS 160/X.

3. RESULTS AND DISCUSSION

The joints were successfully formed for all pressures. The optical micrographs of the bonded assemblies are shown in **Figure 1**.

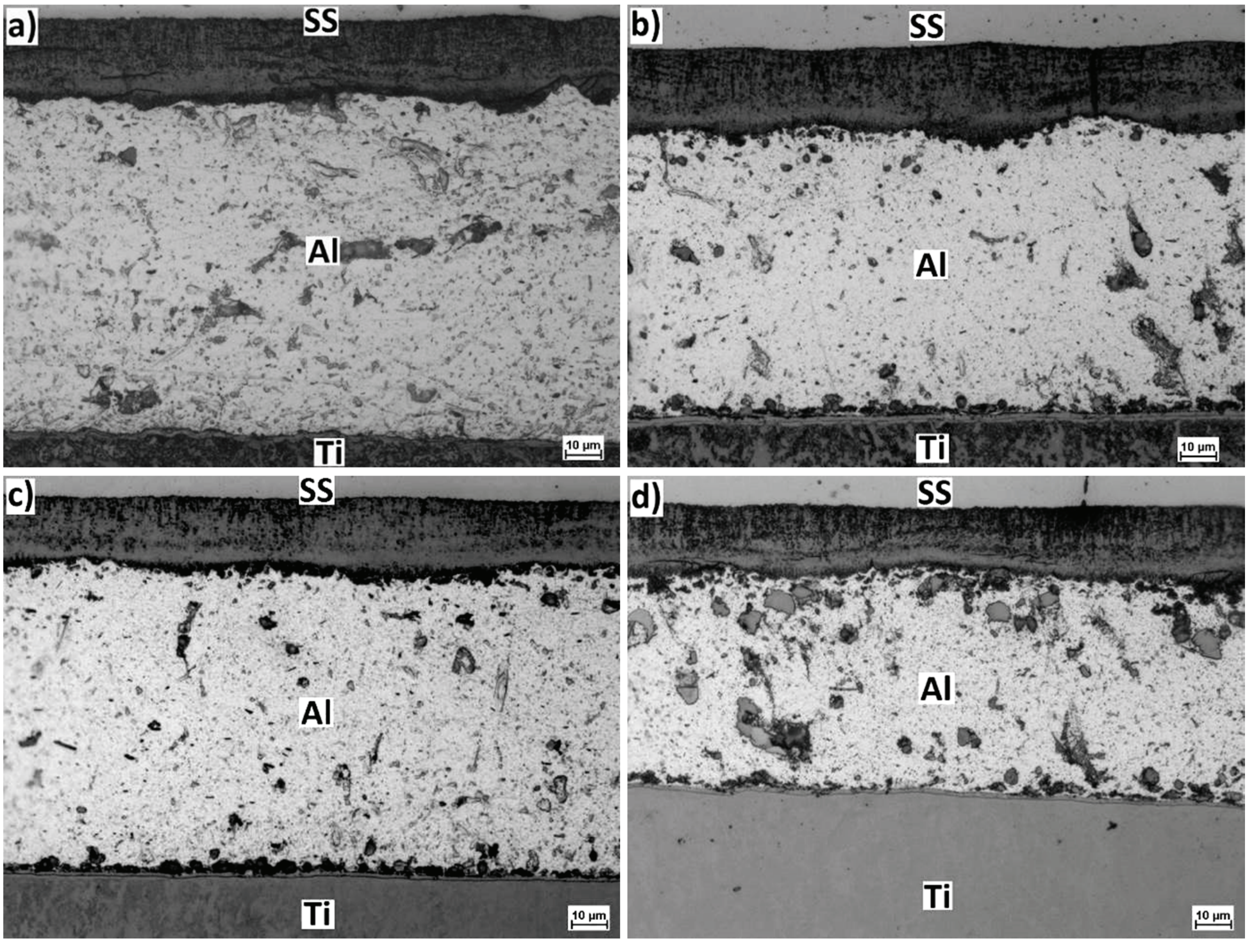

Figure 1 Optical micrograph of the joints prepared using: a) 2, b) 4, c) 6 and d) 8 MPa bonding pressure

From the micrographs, it can be seen that the diffusion interfaces are free from cracks and interface lines are clearly visible. The wide of the diffusion zone on the boundaries with joined materials decreases with an increase in bonding pressure. Since the diffusion bonding temperature is lower than the beta phase transformation the titanium-aluminum site is characterized by the α Ti structure. In addition aluminum is an α stabilizing element and it raises the β phase transformation temperature of Ti [1]. The diffusion zone at the titanium-aluminum interface was revealed as regular and thin layer for all the processing pressure. Two distinct reaction layers have been observed at the stainless steel-aluminum (SS-Al) interface. The diffusion zone at the SS-Al interface is much more larger compared to the Ti-Al side. The thickness of the reaction products at the SS-Al side decreases with increase in the bonding pressure. In order to further characterize the reaction layers of the joint, a SEM images were performed on the reaction layers (**Figure 2**). Regardless of the amount of applied bonding pressure, the combination of reaction layers which formed on the borders of bonded materials were the same. The reaction layer adjacent to the titanium side consisted of 68.62 at. % Al and 31.38 at. % Ti. According to the Ti-Al binary phase diagram it is likely a $TiAl_2$ intermetallic compound. At the stainless steel-aluminum interface the dark shaded layer neighboring to steel 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. %). Under the first layer, second layer adjacent to aluminum has a composition of 74.86 at. % Al and 17.47 at. % Fe with small additions of Cr (5.30 at. %) and Ni (1.18 at. %). According to the chemical analyses and the Fe-Al binary phase diagram, it can be assumed that the phases present in the form of layers at the SS-Al interface are Fe_2Al_5 and $FeAl_3$ with an amount of Cr and Ni admixtures. The wide of intermetallic layers for titanium-aluminum and aluminum-stainless steel interface decreases with the increase in bonding pressure. The thickness measurement of those intermetallic layers is given in **Table 2**.

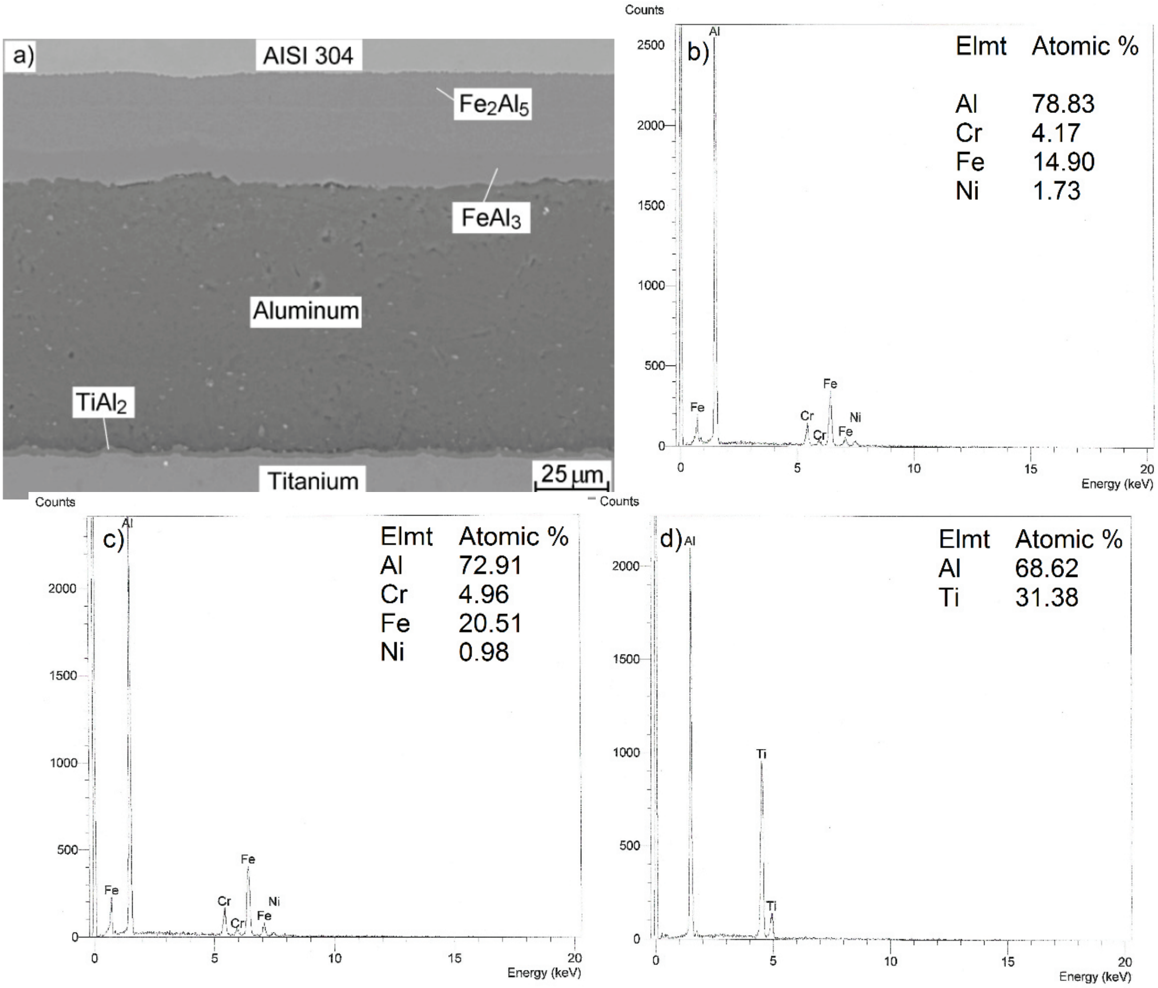

Figure 2 SEM image of diffusion bonded joint performed using compression pressure of 2 MPa and X-ray spectrums for b) $FeAl_3$, c) Fe_2Al_5 and d) $TiAl_2$ intermetallic phases.

Table 2 The thickness measurement of intermetallic phases.

	Bonding pressure (MPa)			
	2	4	6	8
Phases	**Thickness (µm)**			
$TiAl_2$	1.94	1.06	1.52	1.82
Al	96.38	86	81	59.11
$FeAl_3$	9.56	6.69	6.08	5.17
Fe_2Al_5	13.61	18.23	15.04	13.92
Overall	120.19	107	105	80.53

The thickness of $TiAl_2$ intermetallic layer began to reduce when the bonding pressure start to increase, until it reaches a value of 6 MPa. When the higher pressure was applied the thickness of this layer grown to the initial value. Overall thickness of Fe-Al intermetallic phases decrease with increase in joining pressure. However, it seems that the thickness of Fe_2Al_5 grow at the expense of second intermetallic layer at the stainless steel-aluminum side. Overall thickness of aluminum interlayer has been reduced from 120 µm to 80 µm. The last sample diffusion bonded at 8 MPa pressure shows that further increase in the bonding pressure could result in squeezing to much filler metal from the joint, resulting in lack of bonding and excessive deformation of joints and base materials. The shear strength of the diffusion bonded joints with change in bonding pressure is given in **Table 3**.

Table 3 The shear strength of the diffusion bonded joints.

Bonding pressure (MPa)	2	4	6	8
Shear strength (MPa)	21	39	67	88

At the lowest bonding pressure the shear strength of the diffusion couple was low and reached a value of 21.49 MPa. With an increase in the load the shear strength increases and reaches its maximum value of 88 MPa at highest bonding pressure. The increase in shear strength is probably caused by the reducing the thickness of Fe_2Al_5 and $FeAl_3$ intermetallic layers. All samples were separated on the boundary between stainless steel-aluminum side, where formed Fe_2Al_5 and $FeAl_3$ intermetallic phases. He et al. [19] and Yao et al. [7] shows that the dissimilar joint between those materials achieved by using similar bonding parameters are characterized by a shear strength in the range of 34 to 42 MPa. The corrosion resistance test in 3% sodium chloride solution was performed for the samples carried out using 8 MPa bonding pressure due to their highest shear strength during the investigation. The weight loss measurement of diffusion bonded joints of titanium and stainless steel with aluminum interlayer is given in **Table 4**.

Table 4 The weight loss measurement of diffusion bonded joints immersed in a 3% sodium chloride solution.

Immersing time (h)	0	24	48	72	96
Sample weight (g)	5.080	5.075	5.068	5.065	5.059

A considerable galvanic corrosion occurred in the joint area, it has been noticed by a continuous drop in weight of samples immersed in a 3% sodium chloride solution. The average weight loss is 5 mg per day. This test indicates that aluminum as a filler metal for titanium and stainless steel joints characterizes insufficient corrosion resistance in comparison to the base materials. Therefore Lee et al. [6] recommended use Ag-Cu-Pd alloy as intermediate material to joint those materials in highly corrosive environments.

4. CONCLUSIONS

The characterization of the diffusion bonded joints reveals the following:

1) Diffusion bonding pressure is critical factor to control the diffusion zone of the joint. The intermetallic layer $TiAl_2$ was observed at the titanium aluminum side of the diffusion joints. The thicknesses of the $TiAl_2$ intermetallic layer decreases with increase in the bonding pressure to 6MPa. At the stainless steel aluminum interface were formed two layers of Fe_2Al_5 and $FeAl_3$ intermetallic phases. The overall thickness of Fe-Al phases decreases with increase in the bonding pressure. The thickness measurement of intermetallic phases formed on the boundaries of joined materials, indicate that there must be done fundamental studies about the effect of the thickness of the interlayer on the diffusion bonded joints.
2) The aluminum interlayer of 120 μm thickness effectively blocked the diffusion of titanium to stainless steel side, thus prevented from formation of Fe-Ti intermetallic phases on the boundaries of joined materials.
3) The maximum shear strength of 88 MPa was obtained for the diffusion bonded joints performed with highest bonding pressure. The bonding strength increased with the rising of the joining pressure due to the decrease in width of intermetallic phases at the bonding interfaces. The lowest shear strength of 21 MPa was obtained for samples brazed at the lowest pressure.
4) The corrosion resistance test show that aluminum as an interlayer is not the most appropriate metal for joining titanium with stainless steel in corrosive environment.

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