CORROSION RESISTANCE AND MECHANICAL PROPERTIES OF TITANIUM-STAINLESS STEEL JOINTS BONDED BY Al, Cu AND Ni INTERLAYER

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Abstract

The purpose of this study is to compare the dissimilar joints of pure titanium to stainless steel achieved by different intermediate materials like aluminum, copper and nickel. Due to the metallurgical incompatibility between those base materials, it has been very difficult to produce reliable joints due to the formation of FeTi and Fe_2Ti intermetallic compounds. The purpose of using the intermediate material is to reduce and even block the diffusion between titanium and stainless steel. The thickness of those filler metals were 100 μm. The microstructure of the joints were investigated using scanning electron microscopy equipped with an energy dispersive X-ray system (EDS) to determine chemical composition of joint. The maximum values of tensile strengths were obtained for samples prepared using copper as a interlayer. The highest impact energy was achieved for joints performed using aluminum as a filler metal. SEM characterization of the fracture surfaces of the joints shows that the character of fractures are brittle for the samples achieved by copper, nickel and quasi brittle for the specimen prepared using aluminum. The galvanic corrosion test was carried out in a 3.5 % NaCl solution. The potentiodynamic polarization curves show that the higher corrosion potential as well as a lower corrosion current were registered for the joints performed by nickel.

Keywords: Corrosion, mechanical properties, diffusion bonding, titanium, stainless steel

1. INTRODUCTION

Titanium and its alloys have received great attention in nuclear and chemical industry owing to its high strength to weight ratio and excellent corrosion resistance [1, 2]. Because of it properties, titanium (Ti) is the most suitable material in reactor reprocessing plants for fabricating components like dissolver and evaporator, where high concentration of nitric acid and high temperatures are involved [3, 4]. Because other components of reprocessing plants and dissolver are made of 304L stainless steel (SS), there is an obvious requirement to join Ti with SS, as well as economic reasons owing to the high cost of titanium [5]. 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 [6, 7]. Hence, solid state diffusion bonding process is recommended for materials with extremely different physical and mechanical properties [8]. The use of appropriate intermediate materials can also inhibit diffusion of undesired elements [9]. Existing literature and previous attempts showed that to successfully joint titanium with stainless steel is necessary to use of appropriate intermediate materials. 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 [10, 11]. Pure nickel and nickel alloys can be used as a filler material between titanium and stainless steel due to satisfactory corrosion resistance for application at high temperature [12, 13]. Among these materials copper is the most useful metal because it does not form any intermetallic phases with iron (as does aluminum and nickel) [14, 15]. Eroglu et al. [16] reported that Cu-Ti base intermetallic phases have higher plasticity than the Fe-Ti base intermetallics. However when dissimilar materials are joined, particular attention should be paid to the potential corrosion issues arising from the galvanic couple. Galvanic corrosion is an electrochemical process resulting in accelerated and preferential corrosion of one of the metals. Dissimilar materials have different electrochemical potentials, this difference provides the thermodynamic driving force for the onset of galvanic corrosion [17-20]. Since investigated joints are composed of different materials and different structures, a clear estimation of the corrosion resistance of those joints are becoming an essential criterion in evaluating the performance of the joints. The present investigation reports the influence of different intermediate materials as a filler metal on the microstructure, tensile strength, impact energy and corrosion resistance of titanium-stainless steel joints bonded by Al, Cu and Ni interlayer.

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 square rods having 10 x 10 mm width and 2000 mm length, and filler metal foils of 100 μm thickness. The nominal chemical composition at room temperature of these materials is given in **Table 1**.

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

Material	Titanium (Grade 2)	Stainless steel (X5CrNi 18-10)	Aluminum (Al 99.5)	Copper (Cu 99.99)	Nickel (Ni 99.6)
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: 0.390; P: 0.038; S: 0.012; Cr: 18.150; Ni: 8.050; Mo: 0.380	Al: 99.53; Fe: 0.21; Si: 0.16; Zn: 0.05; Cu: 0.03; Ti: 0.02	Cu: 99.99, approximately 0.001 of: Fe; Ni; Zn; Sn; Pb; Sb; As; S;	Ni: 99.57; Cu: 0.11; Co: 0.09; Si: 0.08; Mg: 0.07; Fe: 0.07; Al: 0.01

Specimens of 10 and 27.5 mm length were machined from the titanium and stainless steel rods. The square profile with 10 x 10 mm width was excised from the Al, Cu and Ni foils. The faces of the specimens were prepared by conventional grinding and polishing techniques and final polishing was made with 0.5 μm alumina suspension and colloidal silica with a grain size of 0.05 μm. 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 of 2 MPa along the longitudinal direction was applied at room temperature. Diffusion bonding was carried out in a vacuum furnace Czylok PRC 77/1150. The bonding temperature for the samples with aluminum interlayer was 600 and 900 °C for specimens achieved using copper and also with nickel interlayer. The holding time for all samples was 60 minutes. Vacuum in the furnace was at the level 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 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 and ternary phase diagrams of basic components. The tensile strengths of the boned joints was evaluated at room temperature using a LabTest 5.20SP1 testing machine at a crosshead speed of 10 mm/min. The samples of dimensions 10 x 10 x 55 mm were used for the impact tests. The tests were carried out on an VEB impact-testing machine with a maximum working capacity of 15 J. For each mechanical test, five samples of each material variant were prepared. Fracture surfaces of the samples were observed in a scanning electron microscope (SEM) JEOL JSM 7100F using energy dispersive X-ray spectrometer (EDS) to reveal the nature of failure under loading. The corrosion properties of the specimens were investigated using a CHI 1130A (CH Instruments Inc., Austin, Texas) electrochemical analyzer. The potentiodynamic polarization measurements were conducted at room temperature in a conventional three-electrode cell with the AgCl/Ag electrode as the reference electrode, the platinum wire as the counter electrode and the specimen as the working electrode. The specimens in the form of discs rotated with a speed of 12 revolutions / s. The potentiodynamic polarization measurements were performed in an applied potential range from -1.0 to 0.25 V with a scan rate of 3 mV/s. The tests were carried out in a 3.5 % NaCl solution. Prior to the tests, the specimens were immersed in a 3.5 % NaCl solution for 1000 s to obtain a stable open circuit potential.

3. RESULTS AND DISCUSSION

The results of the microstructure investigations of the joints demonstrated significant diffusion changes and relatively wide diffusion zones on the boundaries with joined metals. The structures of the joints varied importantly depending on the interlayer (**Figure 1**).

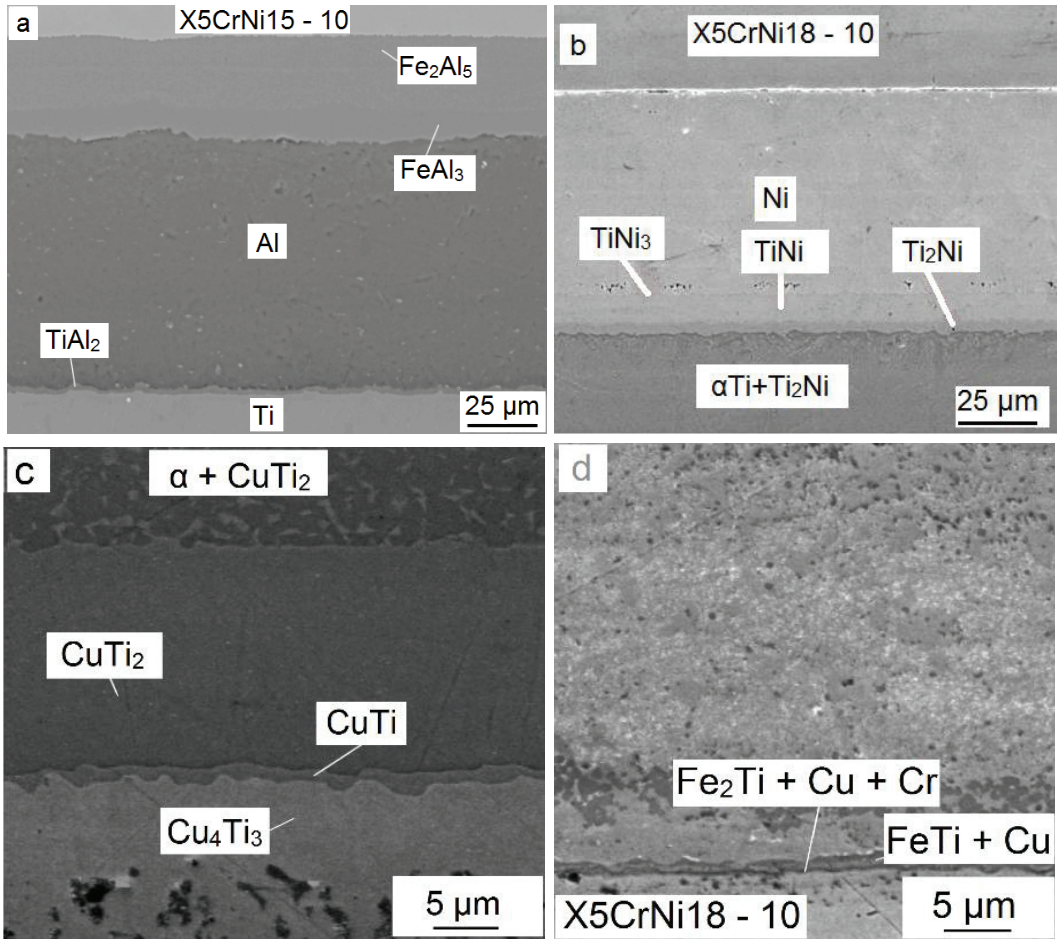

Figure 1 SEM images of diffusion bonded joint by a) Al, b) Ni, c) Cu (Ti-side), d) Cu (SS-side)

As shown in the works [10,12,14], the phases present in copper joints were intermetallics: $CuTi_2$, CuTi, Cu_4Ti_3, FeTi, Fe_2Ti and solid solutions based on intermetallic phases or substrate metals. The intermetallic layers Ti_2Ni, TiNi, $TiNi_3$ were observed at the titanium side in the diffusion boned joints achieved by nickel filler metal. The presence of a solid solution γFe+Ni between nickel and stainless steel was also observed. Using aluminum as a filler metal results in formation intermetallic layer $TiAl_2$ at the titanium aluminum side of the diffusion joints. At the stainless steel aluminum interface were formed two layers of Fe_2Al_5 and $FeAl_3$ intermetallic phases. Due to high migration of copper in the temperature range of 850 to 1000 °C the diffusion of chemical species is easy through interlayer. Therefore titanium can migrate to the stainless steel side and iron can also migrate to the titanium side. Hence, the copper interlayer of 0.1 mm thickness cannot prevent the formation of brittle Fe-Ti base intermetallic phases, what can be achieved by using aluminum and nickel interlayers. The tensile strength of the diffusion bonded joints achieved by different intermediate materials is given in the **Table 2**.

Table 2 The tensile strength of the diffusion bonded joints

Filler metal	Al	Cu	Ni
UTS (MPa)	131	343	247

The maximum tensile strength of 343 MPa was obtained for the diffusion bonded joints performed by using the copper foil. The bonding strength decreased with use of aluminum and nickel foil as a filler material between titanium and stainless steel. This can be caused by remaining pure metal from aluminum and nickel foil in the middle of the joint. The lowest tensile strength of 131 MPa was obtained for samples joined using aluminum. The results of the impact test of dissimilar joints of titanium and stainless steel with different metal foils are given in **Table 3**.

Table 3 The impact test of the diffusion bonded joints

Filler metal	Al	Cu	Ni
Impact energy (J)	0.35	0.30	0.15

The highest value of impact energy (0.35 J) was observed for samples obtained by aluminum interlayer. Probably this was due to unreacted aluminum in the middle section of the investigated joint, because aluminum has the highest plasticity between used materials. The minimum impact energy of 0.15 J was obtained for the diffusion bonded joints performed by using nickel foil due to the appearance of the Kirkendall voids at the Ti-Ni interface. The fracture surfaces of the specimens processed by Al, Cu and Ni foil are shown in **Figure 2**. The bright area of Al joint (**Figure 2a**) was comprised of 76.09 at.% Al and 18.24 at.% Fe with small amounts of Cr (4.66 at.%) and Ni (1.01 at.%) and the dark shaded area consists of 72.94 at.% Al and 19.91 at.% Fe with small amounts of Cr (5.62 at.%) and Ni (1.53 at.%).The composition indicated the presence of $FeAl_3$ and Fe_2Al_5 intermetallic phase. For joints processed by Cu foil (**Figure 2b**), the fracture was comprised of 54.38 at.% Cu and 45.62 at.% Ti. According to the Ti-Cu binary phase diagram it is likely a CuTi intermetallic phase. Both the shaded matrix and the bright line of diffusion bonded joint achieved by Ni (**Figure 2c**) were comprised of 66.80 at.% Ti and 33.20 at.% Ni. It seems to be Ti_2Ni.

The fracture surfaces of the specimens processed by Al foil were quasi brittle. The character of fractures was brittle for the samples achieved by copper and nickel. Potentiodynamic polarization curves for the boned samples prepared by the Al, Cu and Ni fillers are shown in **Figure 3**. The values of corrosion potential were determined to be -0.618, -0.409, -0.383 V for the samples boned with the Al, Cu and Ni fillers, respectively. The corrosion currents were estimated to be as follow: for joints with Al 0.10788 mA/cm^2, with Cu 0.01105 mA/cm^2 and with Ni 0.01057 mA / cm^2. The joints boned with copper as well with the nickel have shown very similar behavior in terms of the corrosion potential, and dissolution current density.

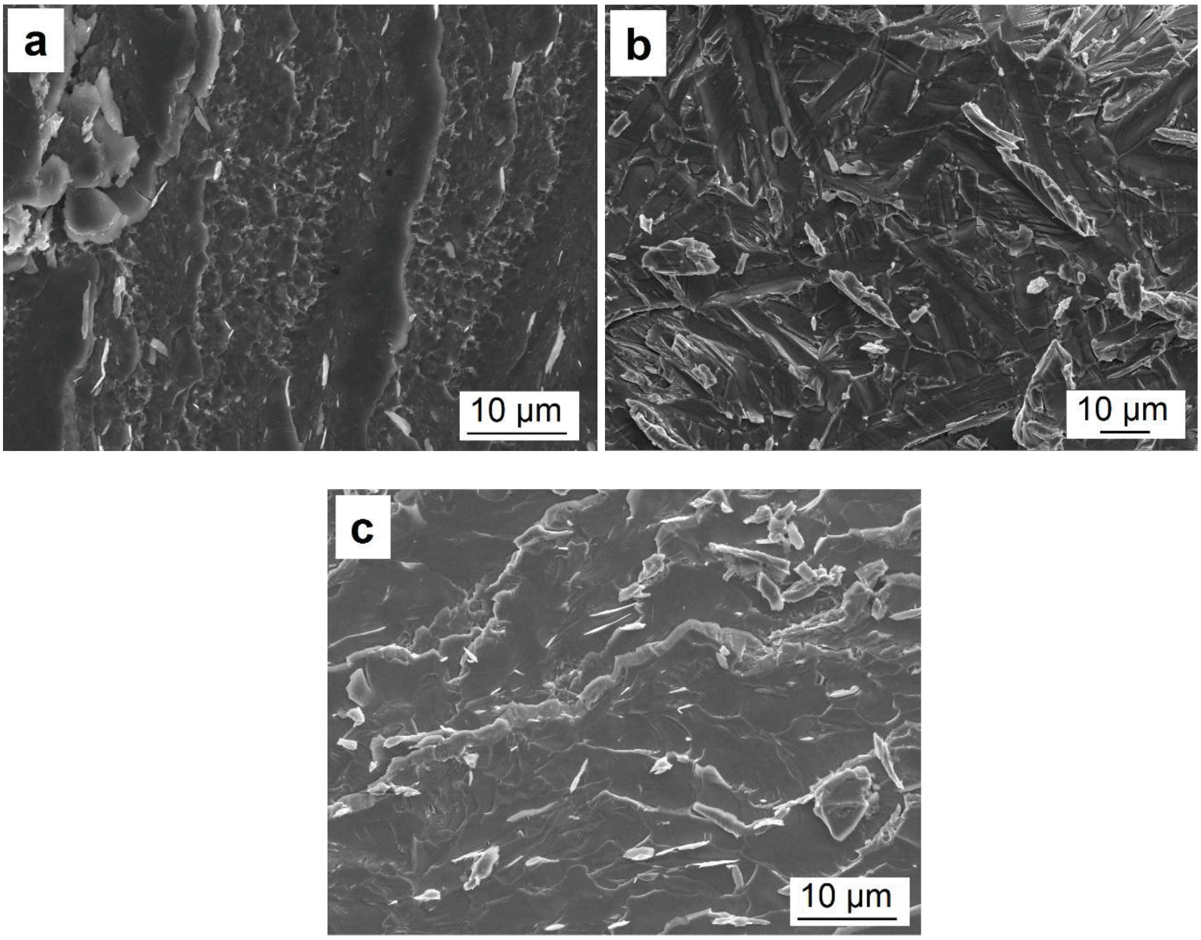

Figure 2 Fracture surfaces of the brazed joints processed by a) Al, b) Cu and c) Ni foils

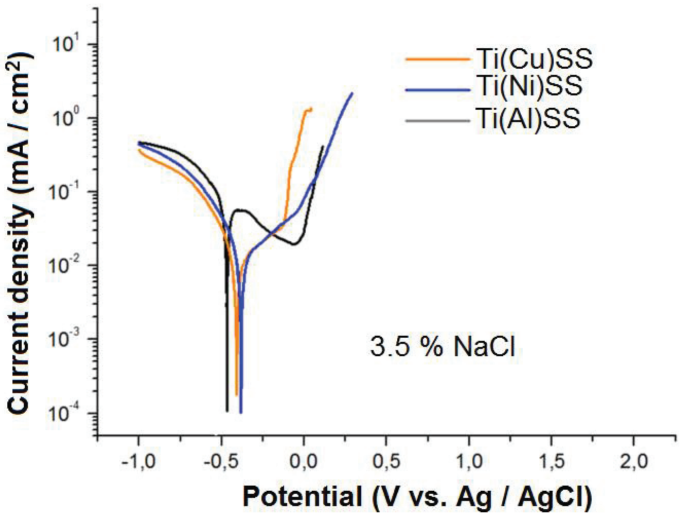

Figure 3 Polarization curves recorded in 3.5 % NaCl solution for diffusion bonded joints

The highest corrosion potential as well as the lowest corrosion current was observed for the sample boned by the nickel interlayer, according to the literature studies [17-20] such a result indicates that this joint has the highest corrosion resistance among investigates diffusion boned joints. However, Lee et al. [17, 18] reported that Ag and alloy fillers have higher resistance to corrosion.

4. CONCLUSIONS

The use of appropriate intermediate material in diffusion bonded joint between titanium and stainless steel is critical factor to control the microstructure as also mechanical properties of the joint. As the investigation show, the phases present in joints were intermetallics and solid solutions based on intermetallic phases or substrate metals. The aluminum and nickel interlayer of 100 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. Copper have not managed to do so, however it obtained maximum tensile strength of 343 MPa and achieved second best result in impact test (0.30 J). The fracture surfaces of the joints show that the character of fractures are brittle for the samples achieved by copper, nickel and quasi brittle for the specimen prepared by aluminum. The corrosion test show that the nickel as a interlayer is the most appropriate metal among tested materials for joining titanium with stainless steel in corrosive environment. However, joints boned with copper have shown very similar behavior to the nickel in terms of the corrosion potential, and dissolution current density. This shows that copper also can be successfully used in corrosive environment. According to the results of present investigation copper seems to be the most appropriate material as filler metal to join titanium with stainless steel.

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