WEAR RESISTANCE PROPERTIES OF DIFFUSION BONDED JOINTS BETWEEN TITANIUM AND STAINLESS STEEL OBTAINED BY Al, Cu AND Ni INTERMEDIATE MATERIALS

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Abstract

In the present study, commercial pure titanium (Grade 2) was joined to the stainless steel (X5CrNi18-10) by diffusion bonding using different intermediate materials like aluminum, copper and nickel. The thickness of those filler metals were 100 μm. The use of intermediate materials to create diffusion bond minimize thermal expansion mismatch, to reduce joining temperature and pressure and to inhibit diffusion of undesired elements to the base materials. However it also can cause formation of numbers of intermetallic phases. The investigation was focused on comparing the wear resistance of the obtained diffusion joints. The microstructure of the joints was investigated using scanning electron microscopy equipped with an energy dispersive X-ray system (EDS) to determine chemical composition of joint. The structures of the joints varied importantly depending on the interlayer. However in the samples obtained by nickel interlayer at the borders of materials were observed Kirkendall voids. Value of friction force and wear resistance of diffusion bonded joints were carried out by block-on-ring frictional pair, preformed on the tribological tester T-05. The study was carried out under conditions of technically dry friction for the concentrated sliding contact loaded with 300 N. Friction distance for each test was 400 m. The results show that the maximum values of friction coefficient and mass loss was obtained for joints with nickel interlayer.

Keywords: Wear resistance, microstructure, diffusion bonding, titanium, stainless steel

1. INTRODUCTION

Due to the excellent anti-corrosive properties, high strength to weight ratio, good fatigue properties and satisfactory strength properties, titanium and its alloys have been widely used in sports tool manufacturing, chemical, food, biomedical and aerospace industries [1, 2]. Also titanium is the most suitable material in reactor reprocessing plants for fabricating components like dissolver and evaporator in nuclear industry, where high concentration of nitric acid and high temperatures are involved [3]. Austenitic stainless steels are widely employed in nuclear reactors, biomedical implants, machinery for chemical and food processing industries. In nuclear industries, engineering components namely control rod actuator mechanisms and valves are made of stainless steel [4, 5]. Because titanium (Ti) and stainless steel (SS) are mostly used in the same industries, where good mechanical properties as well as high corrosion resistance are required, there is a strong indication to bonding these materials together. In addition, joining Ti with SS allows reduce the cost of production, because stainless steel is much cheaper than titanium [6]. The most appropriate way to joint materials with extremely different physical and mechanical properties is solid state diffusion bonding with use of metal interlayer [7]. The use of intermediate materials to create diffusion bond minimize thermal expansion mismatch, reduce joining temperature and pressure, inhibit diffusion of undesired elements to the base materials. However it also can cause formation of numbers of intermetallic phases [8]. These phases are not beneficial in terms of joint strength, however, as a result of their formation, the hardness in the joint area will increase significantly which may translate into an increase in wear resistance [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]. 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 [11]. Among these materials copper is the most useful metal because it does not form any intermetallic phases with iron (as does aluminum and nickel) [12]. Eroglu et al. [13] reported that Cu-Ti base intermetallic phases have higher plasticity than the Fe-Ti base intermetallics. The purpose of this research was to investigate if the different intermediate materials in diffusion joints between titanium and stainless steel affect the change in the friction coefficient and the overall mass loss of the bonded samples.

2. EXPERIMENTAL PROCEDURE

The base materials used for 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 compositions at room temperature of these materials are 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 20 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. 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 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. Then the samples were cut to the dimensions according to the ASTM standard G77. Friction and wear tests were carried out on T05 tribological tester with the frictional pair: “block-on-ring”. Frictional and wear tests were carried out with the following parameters: contact type: concentrated linear contact; ring width: 6.35 mm; ring diameter: 35 mm; type of movement: sliding, rotating; rotational speed of the ring 218 rot./s; load force: 300 N; friction distance: 400 m; lubrication: none. The counter specimens wear made of steel with hardness of HRC 63. Each sample was tested using a new counter specimen. The samples were observed in a light microscope Nikon Eclipse MA200 to to examine the wear tracks and profile of worn surface. The weight loss during the wear test was measured with using analytical balance Radwag AS 160 / X.

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**).

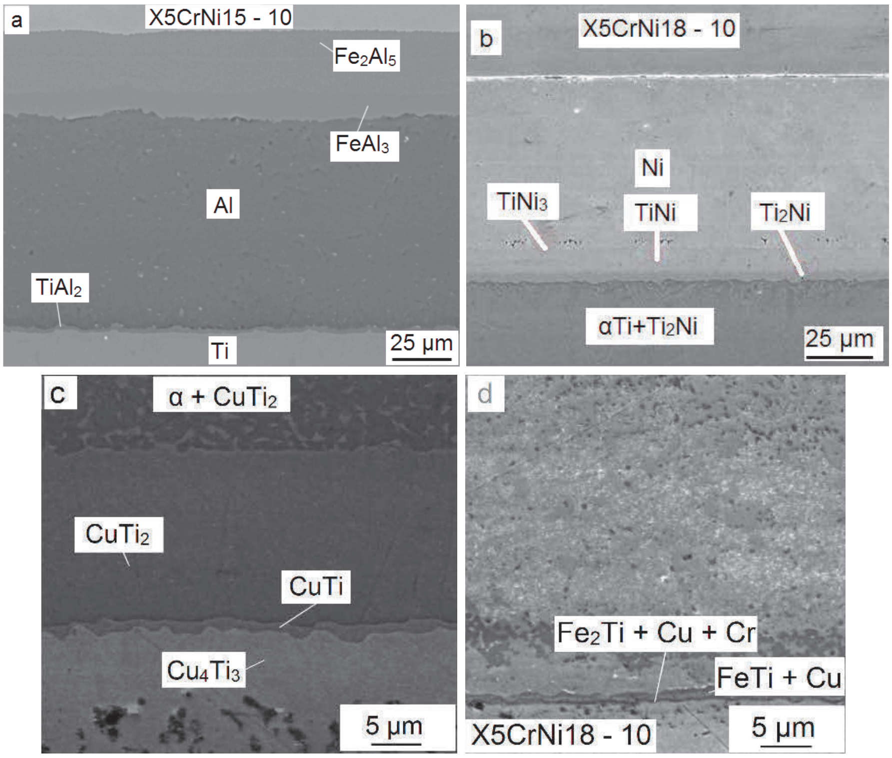

Figure 1 SEM images of diffusion bonded joint by a) Al, b) Ni, c) Cu (Ti-side) and d) Cu (SS-side)

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 resulted 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 wear track in the middle section of the joint achieved by aluminum interlayer was wider than those in base materials of the joint (**Figure 2**). This was due to the fact that the Al interlayer was not entirely consumed during the formation of the joints between based materials and aluminum interface. In that case pure aluminum which was used to create joints is much more softer then steel counter specimen and base materials. As shown in the **Figure 2** the area between the titanium and copper interlayer is less worn then at the stainless steel area. This could indicate that the Fe_2Ti intermetallic phase start to crumbled during the friction test, it also seems to confirm that Cu-Ti base intermetallic phases have higher plasticity than the Fe-Ti base intermetallics as shown in the article [13]. In the case of a joint obtained with a nickel intermediate material, it is clearly visible that in the middle section of the joint a part of the interlayer was torn out as well as in the border area between stainless steel and nickel interlayer was created ditch.

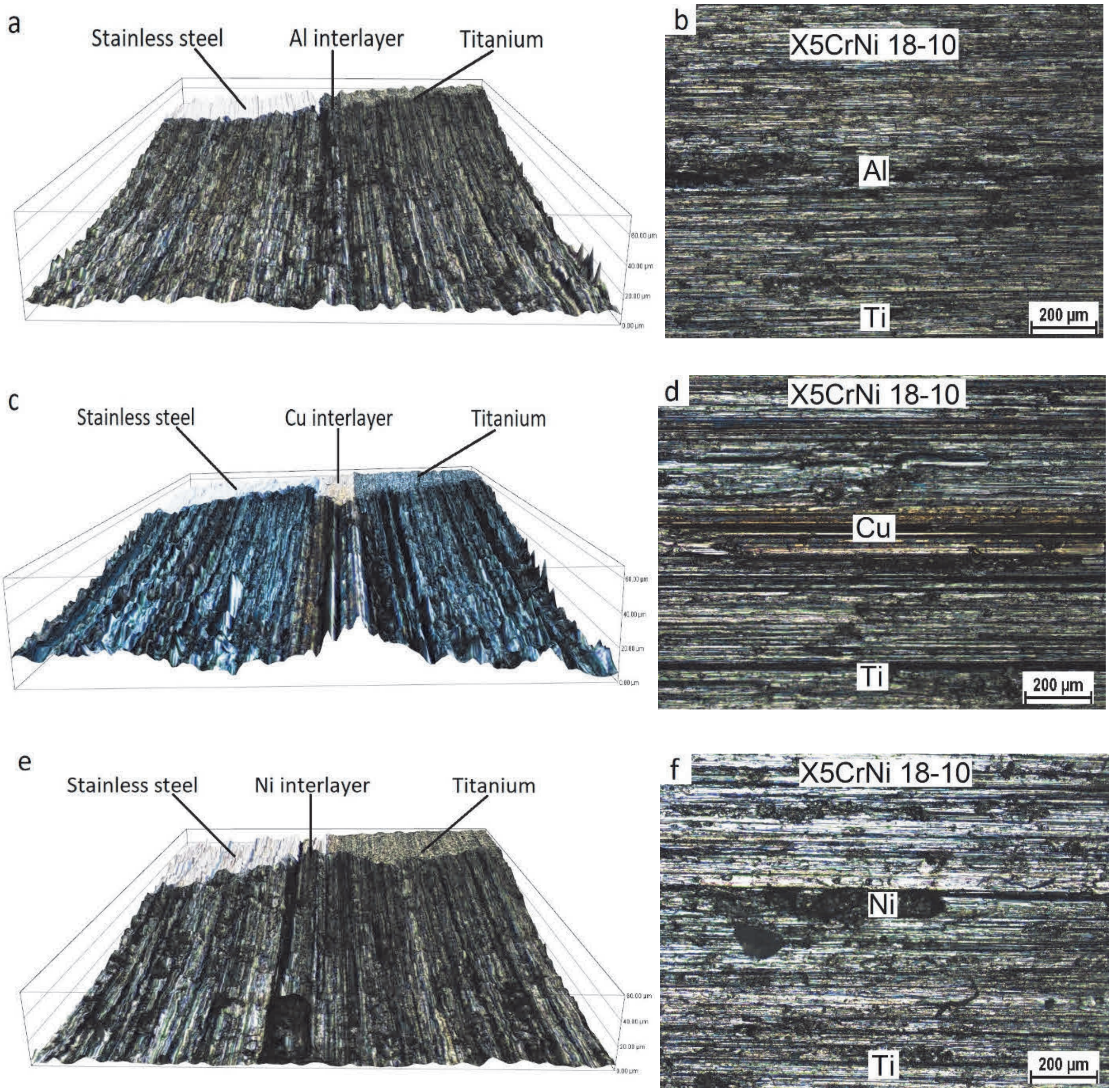

Figure 2 Optical micrographs of the wear tracks and profile of worn surface after a sliding distance of 400 m for the diffusion bonded joints between titanium and stainless steel obtained by different metal interlayer a), b) for Al interlayer, c), d) for Cu interlayer and e), f) for Ni interlayer.

It could have been caused by Kirkendall voids present in area between base materials and interlayer. The results of the wear test on the tribological tester T-05 are shown as a chart of friction coefficient (COF) as a function of sliding distance on the **Figure 3**. The average values of friction coefficient vs. frictional distance were determined on the basis of measurements of frictional and loading forces according to the Amontons-Coulomb law. The COF for the joint achieved by nickel interlayer exhibited significant fluctuations which may due to the chipped off the parts of middle section of the joint where intermetallic phases have been identified (Ti_2Ni, TiNi, $TiNi_3$). That can explain the highest value of friction coefficient among the investigated joints. The average value for diffusion bonded joints obtained by nickel intermediate material was 0.69. The friction coefficient for Ti(Cu)SS joints exhibits a quick increase during the first 25 meters of sliding distance followed by a decrease until it reaches a steady value close to the average value (0.47) for this sample. That can explain the highest value of friction coefficient among the investigated joints.

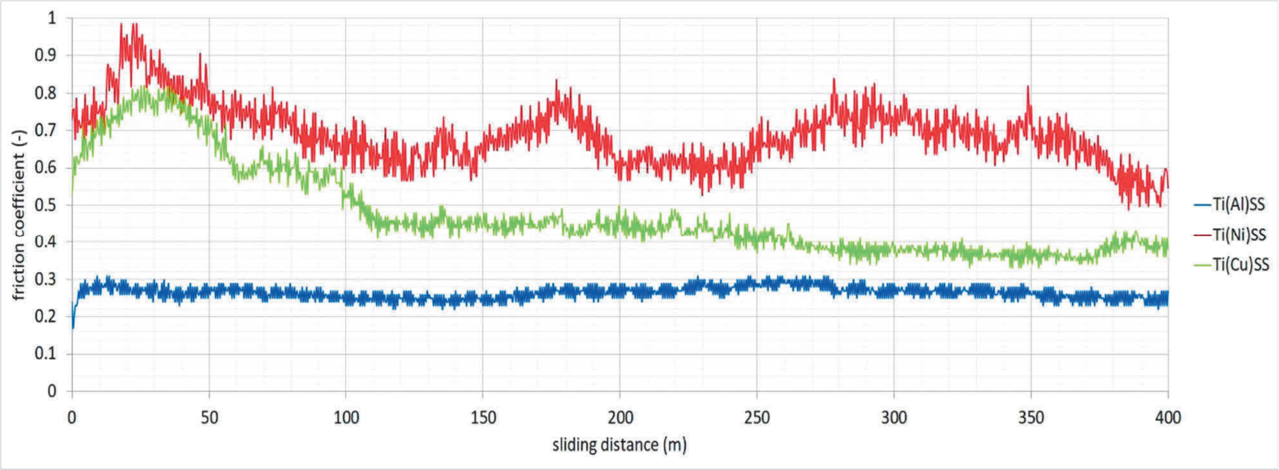

Figure 3 Change of friction coefficient in the function of sliding distance

The average value for diffusion bonded joints obtained by nickel intermediate material was 0.69. The friction coefficient for Ti(Cu)SS joints exhibits a quick increase during the first 25 meters of sliding distance followed by a decrease until it reaches a steady value close to the average value (0.47) for this sample. The evolution of the coefficient of friction for this joint looks like a two phase wear. The first stage is caused by the formation of wear debris, which probably came from the area between stainless steel and copper interlayer, inducing a rise in the coefficient of friction. During the steady state, a low coefficient of friction is measured. It can be caused by debris get trapped in the wear track or are all pushed out. In comparison to joints made with the participation of copper and nickel, the samples obtained by an aluminum interlayer characterized by the most stable and the lowest value of the friction coefficient as the graph indicates. Its average value was 0.26. The results of mass loss measurement of the titanium-stainless steel diffusion joints and the corresponding steel counter-specimens are presented in **Figure 4**.

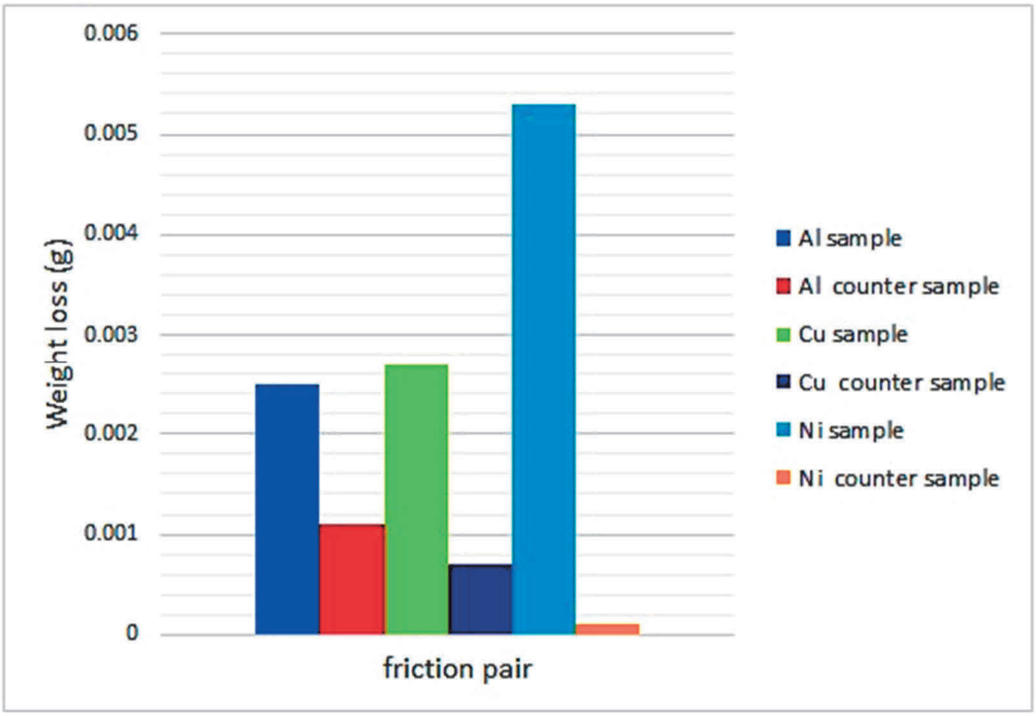

Figure 4 Mass loss of the diffusion bonded joints and their counter-specimens

In all the cases, the weight losses of the diffusion bonded joints were greater than the counter samples. The highest mass loss (5.3 mg) was obtained for the joints achieved by nickel intermediate material. Such a result could be due to fact that the middle section of the joint where the intermetallic phases have been identified, start to crumble during the wear test and those particles of additional materials could act as an abrasive material as an addiction to the steel counter specimen. This also can explain the negligible mass loss on the counter specimen matching with sample made by nickel interlayer. The mass loss in the remaining frictional couples were similar, however the lowest mass loss (2.5 mg) was noted for the sample made with the participation of aluminum.

4. CONCLUSIONS

The aim of this investigation was to check if the used of different metals as a bonding phase in diffusion joints between titanium and stainless steel will affect the degree of wear and friction coefficient. As a result shows, the coefficient of friction and mass loss obtained different values for individual samples even though the intermediate materials have a thickness of 100 µm. The highest value of friction coefficient (0.69) and weight loss (5.3 mg) were noted for joints prepared by nickel interlayer. Such a result could be due to fact that the middle section of the joint where the intermetallic phases have been identified, start to crumble during the wear test and could act as an abrasive material causing an increase in the coefficient of friction and weight loss. The difference between the weight loss of samples made by aluminum and copper interlayer was small. However, there was a large difference between coefficient of friction for these samples. This could indicate that the Fe_2Ti intermetallic phase in the diffusion joints made by copper interlayer start to crumbled during the friction test and get trapped in the wear track of steel ring causing the coefficient value to increase for this sample. The lowest weight loss (2.5 mg) and friction coefficient (0.26) was noted for joints with aluminum spacer. This could indicate that the diffusion bonded joints between titanium and stainless steel obtained by aluminum interlayer has the best exploitation properties among investigated joints.

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