Bartłomiej SZWED[*], **Marek KONIECZNY**[*]

EVALUATION OF WEAR AND CORROSION RESISTANCE OF TITANIUM AND STAINLESS STEEL JOINTS MADE OF Al, Cu AND Ni

OCENA ODPORNOŚCI NA ZUŻYCIE I KOROZJĘ ZŁĄCZY WYKONANYCH POMIĘDZY TYTANEM A STALĄ NIERDZEWNĄ ZA POŚREDNICTWEM Al, Cu ORAZ Ni

Key words: wear resistance, corrosion, diffusion bonding, titanium, stainless steel.

Abstract In the present study, commercial pure titanium (Grade 2) was joined to the stainless steel (X5CrNi18-10) by diffusion bonding using aluminium, copper, and nickel as interlayers (100 µm). The investigation focuses on comparing the wear and corrosion 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 the chemical composition of joint. The value of friction force and the 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. The friction distance for each test was 400 m. The results show that the maximum values of the friction coefficient and mass loss were obtained for joints with a nickel interlayer. The galvanic corrosion tests were carried out in 0.5 M Na_2SO_4 solution acidified to pH 1 with a sulphuric acid solution. The potentiodynamic polarization curves show that the lowest corrosion current was registered for the joints performed by copper.

Słowa kluczowe: odporność na zużycie, korozja, spajanie dyfuzyjne, tytan, stal nierdzewna.

Streszczenie W niniejszej pracy połączono czysty tytan (Grade 2) ze stalą nierdzewną (X5CrNi18-10) poprzez spajanie dyfuzyjne z użyciem międzywarstw z aluminium, miedzi oraz niklu (100 µm). Badanie koncentruje się na porównaniu odporności na zużycie i korozję uzyskanych złączy dyfuzyjnych. Mikrostrukturę połączeń badano za pomocą skaningowej mikroskopii elektronowej wyposażonej w system dyspersji energii (EDS) w celu określenia składu chemicznego spoiny. Wartość siły tarcia oraz odporności na ścieranie połączeń dyfuzyjnych została określona za pomocą testera tribologicznego T-05, który pracował w układzie pary ciernej typu „blok–pierścień”. Badania przeprowadzono w warunkach tarcia technicznie suchego dla styku ślizgowego obciążonego 300 N. Droga tarcia dla każdego testu wynosiła 400 m. Wyniki wskazują, iż najwyższą wartość współczynnika tarcia i ubytku masy uzyskano dla połączeń z niklową przekładką. Badanie odporności na korozję elektrochemiczną przeprowadzono w 0,5 M roztworze Na_2SO_4 zakwaszonym do pH 1 kwasem siarkowym. Potencjodynamiczne krzywe polaryzacji wskazują, że najniższą wartość prądu korozyjnego zarejestrowano dla połączeń wykonanych przy użyciu przekładki miedzianej.

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[*] Kielce University of Technology, Faculty of Mechatronics Engineering, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland.

INTRODUCTION

Titanium and its alloys have received great attention in nuclear and chemical industries due to its high strength to weight ratio and excellent corrosion resistance [**L. 1, 2**]. Because of its properties, titanium (Ti) is the most suitable material in reactor reprocessing plants for fabricating components like dissolvers and evaporators, where high a concentration of nitric acid and high temperatures are involved [**L. 3, 4**]. Because other components of reprocessing plants and dissolvers are made of 304L stainless steel (SS), there is an obvious requirement to join Ti with SS, as well as economic reasons due to the high cost of titanium [**L. 5**]. Traditional fusion welding of dissimilar materials results in different problems, like the distortion of components, the formation of stress concentration sites, the 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, making them very difficult to weld, because they can easily pick up nitrogen and oxygen from the atmosphere [**L. 6, 7**]. Hence, the solid state diffusion bonding process is recommended for materials with extremely different physical and mechanical properties [**L. 8**]. The use of appropriate intermediate materials can also inhibit diffusion of undesired elements [**L. 9**]. However, it also can cause the formation of several intermetallic phases [**L. 10**]. 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 [**L. 11**]. Existing literature and previous attempts showed that, to successfully joint titanium with stainless steel, it is necessary to use the appropriate intermediate materials. Aluminium can be considered as a useful interlayer due to the lowering of bonding parameters for solid state diffusion bonding, and aluminium has certain erosion resistance and excellent plasticity [**L. 12, 13**]. Pure nickel and nickel alloys can be used as a filler material between titanium and stainless steel due to satisfactory corrosion resistance for applications at high temperatures [**L. 14, 15**]. Among these materials, copper is the most useful metal, because it does not form any intermetallic phases with iron (as does aluminium and nickel) [**L. 16, 17**]. Eroglu et al. [**L. 18**] reported that Cu-Ti base intermetallic phases have higher plasticity than the Fe-Ti base intermetallic phases. 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, and this difference provides the thermodynamic driving force for the onset of galvanic corrosion [**L. 19–22**]. Since investigated joints are composed of different materials and different structures, clear estimations 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 interlayers.

MATERIALS AND METHODOLOGY

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 10×10 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 of the base materials (accordingly to certificates)
Tabela 1. Skład chemiczny zastosowanych materiałów (zgodnie z certyfikatami)

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 profiles with 10×10 mm widths were 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 a steel clamp and

Fig. 1. Czylok PRC 77/1150 Vacuum furnace

Rys. 1. Piec próżniowy Czylok PRC 77/1150

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 (**Fig. 1**).

The bonding temperature for the samples with aluminium interlayer was 600 and 900°C for specimens achieved using copper and also with nickel interlayers. The holding times for all samples were 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 percentage 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" (**Fig. 2**).

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; and, lubrication: none. The counter specimens were made of steel with a 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 examine the wear tracks and the profile of the worn surface. The weight loss during the wear test was measured using an analytical balance Radwag AS 160/X. The corrosion properties of the specimens were investigated using a CHI 1130A (CH Instruments Inc., Austin, Texas) electrochemical analyser. The potentiodynamic polarization measurements were conducted at room temperature in a conventional three-electrode cell with the AgCl/Ag electrode as the

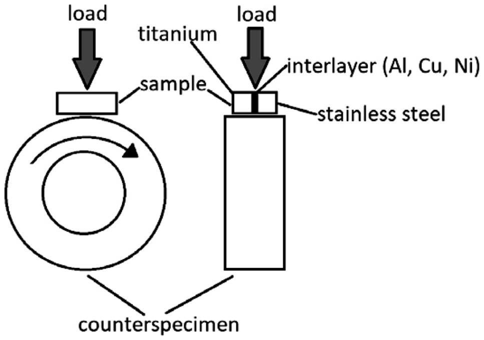

Fig. 2. Block-on-ring frictional pair used in the tests (T05 tester)

Rys. 2. Schemat badanego węzła tarcia typu rolka–klocek – tester T05 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. 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 0.5 M Na_2SO_4 solution. Prior to the tests, the specimens were immersed in a 0.5 M Na_2SO_4 solution acidified to pH 1 with sulphuric acid for 1000 s to obtain a stable open circuit potential.

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 significantly, depending on the interlayer (**Fig. 3**).

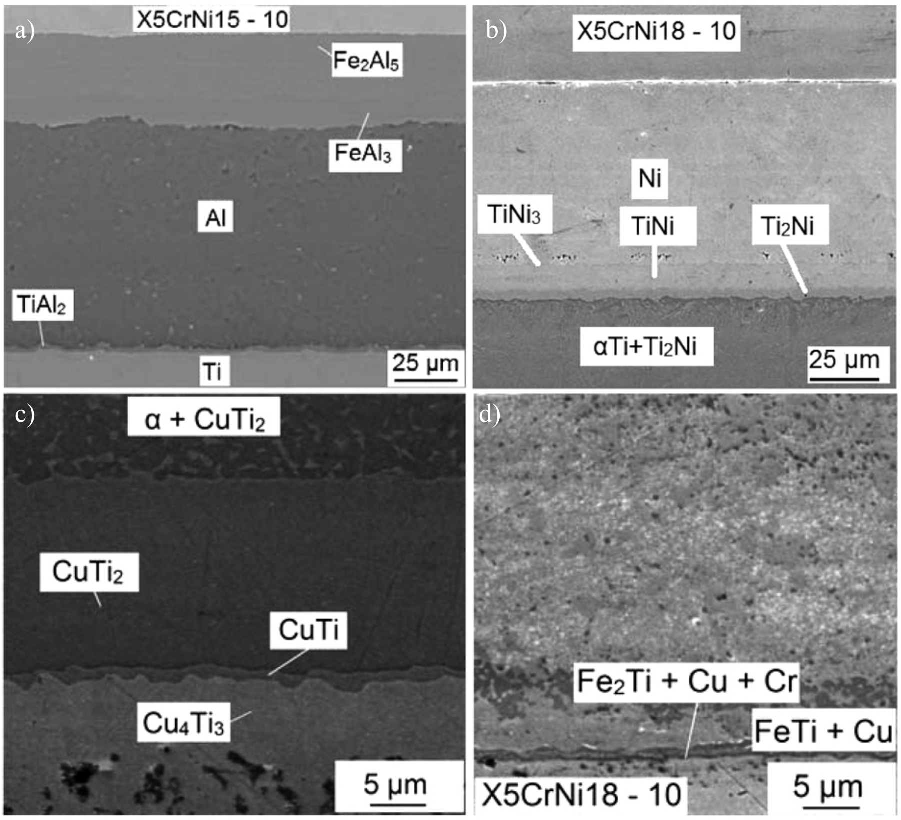

Fig. 3. SEM images of diffusion bonded joint by a) Al, b) Ni, c) Cu (Ti-side) and d) Cu (SS-side)

Rys. 3. Mikrostruktury (SEM) połączń dyfuzyjnych wykonanych za pośrednictwem a) Al, b) Ni, c) Cu (Ti-strona) and d) Cu (SS-strona)

As shown in the works [**L. 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, and $TiNi_3$ were observed on 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 aluminium as filler metal results in the formation of an intermetallic layer $TiAl_2$ on the titanium aluminum side of the diffusion joints. At the stainless steel aluminium interface two layers of Fe_2Al_5 and $FeAl_3$ intermetallic phases were formed. Due to high migration of copper in the temperature range of 850 to 1000°C, the diffusion of chemical species is easy through the 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, which can be achieved by using aluminium and nickel interlayers. The wear track in the middle section of the joint achieved by the aluminium interlayer was wider than those in the base materials of the joint (**Fig. 4** and **Fig. 5**).

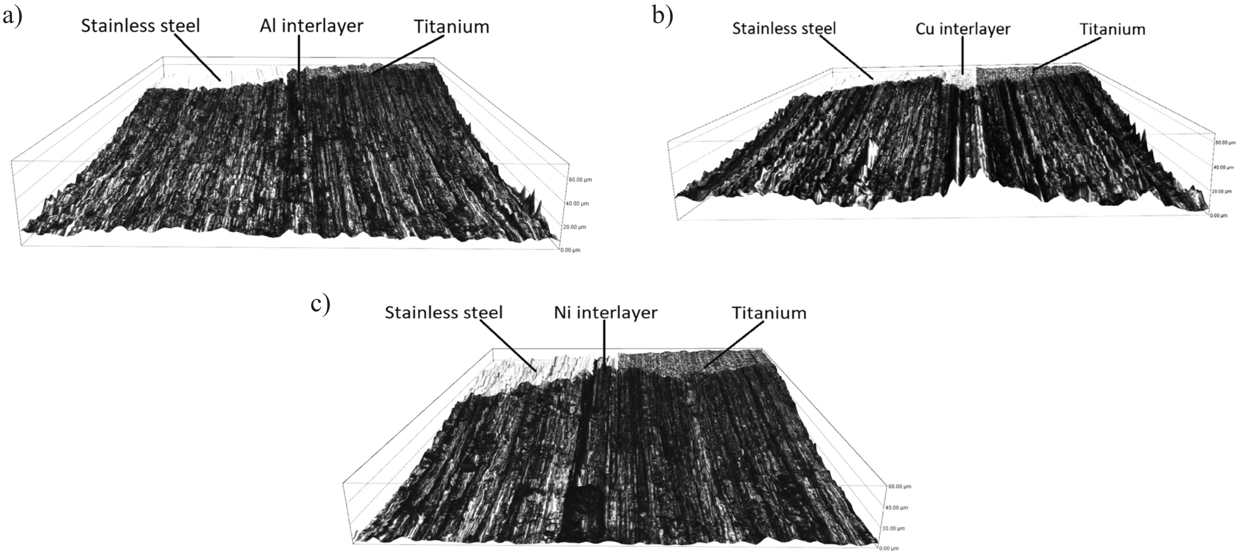

Fig. 4. Optical micrographs of the profile of worn surface for the diffusion bonded joints between titanium and stainless steel obtained by different metal interlayer a) Al interlayer, b) Cu interlayer and c) Ni interlayer

Rys. 4. Topografia powierzchni złączy dyfuzyjnych powstałych pomiędzy między tytanem a stalą nierdzewną uzyskanych za pośrednictwem międzywarstw a) Al, b) Cu oraz c) Ni

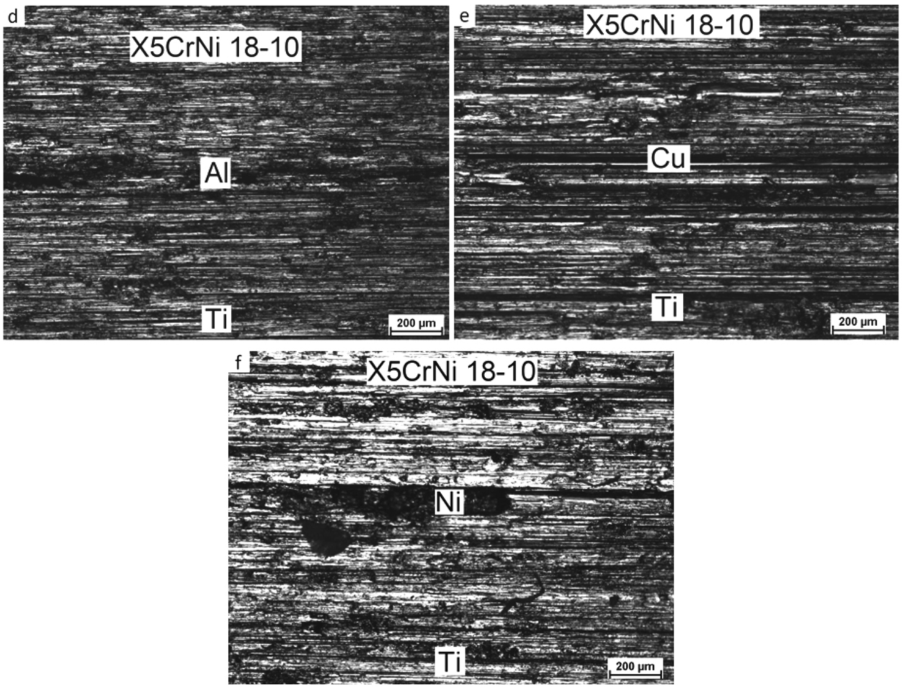

Fig. 5. Optical micrographs of the wear tracks for the diffusion bonded joints between titanium and stainless steel obtained by different metal interlayer d) Al interlayer, e) Cu interlayer and f) Ni interlayer

Rys. 5. Ślady zużycia oraz topografia powierzchni złączy dyfuzyjnych powstałych pomiędzy między tytanem a stalą nierdzewną uzyskanych za pośrednictwem międzywarstw d) Al, e) Cu oraz f) Ni

This was due to the fact that the Al interlayer was not entirely consumed during the formation of the joints between based materials and aluminium interface. In that case, pure aluminium, which was used to create the joints, is much softer than the steel counter specimen and base materials. As shown in **Figs. 4** and **5**, 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 starts to crumble during the friction test, and 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 [**L. 18**]. 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, and in the border area between stainless steel and nickel interlayers, a ditch was created. It could have been caused by Kirkendall voids present in the area between the base materials and the interlayer. The results of the wear test on the tribological tester T-05 are shown as a chart of the friction coefficient (COF) as a function of sliding distance on **Fig. 6**.

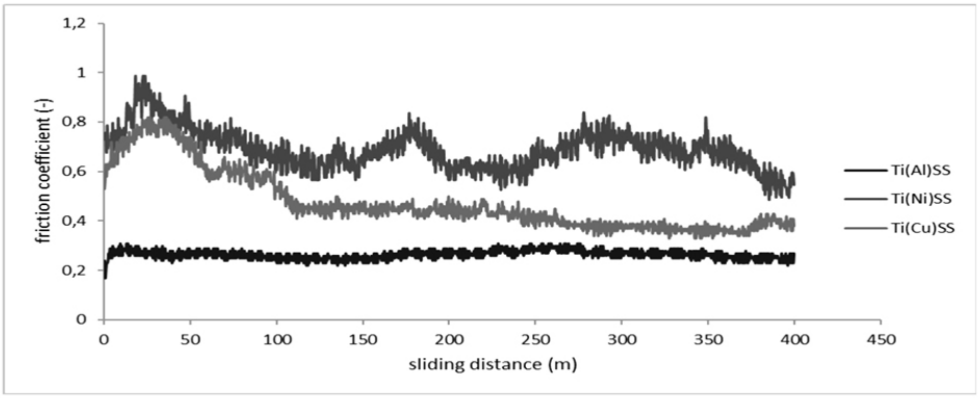

Fig. 6. Change of friction coefficient in the function of sliding distance
Rys. 6. Zmiana współczynnika tarcia w funkcji drogi tarcia

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 of the parts of the 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. 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 being all pushed out. In comparison to joints made with the participation of copper and nickel, the samples obtained by an aluminium interlayer are 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 measurements of the titanium-stainless steel diffusion joints and the corresponding steel counter-specimens are presented in **Fig. 7**.

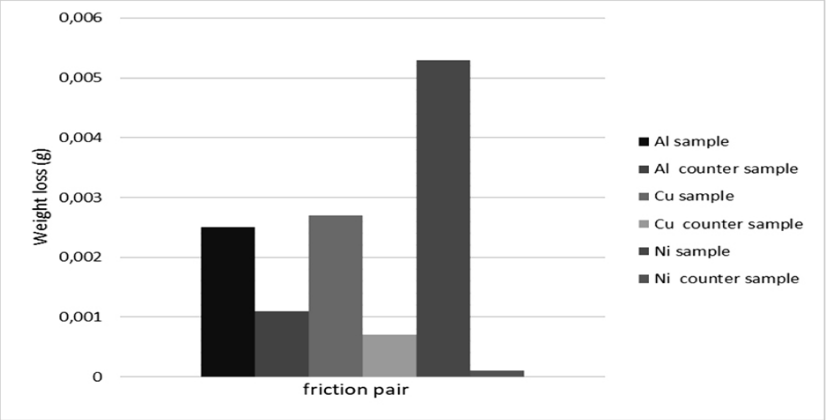

Fig. 7. Mass loss of the diffusion bonded joints and their counter-specimens
Rys. 7. Ubytek masy badanych próbek oraz przeciwpróbkek stalowych

In all 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. This 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 losses 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 aluminium. Potentiodynamic polarization curves for the bonded samples prepared by the Al, Cu, and Ni fillers are shown in **Fig. 8**.

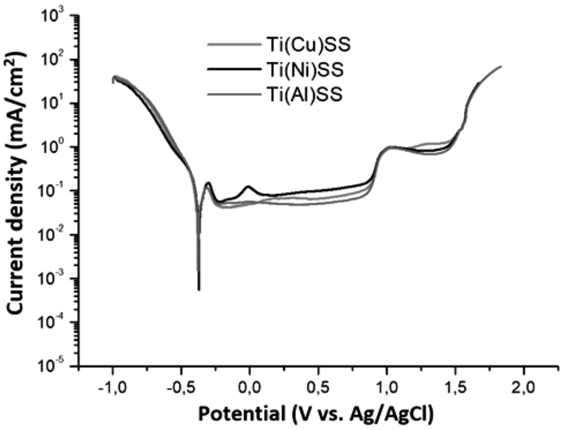

Fig. 8. Polarization curves recorded in 0.5 M Na_2SO_4 (pH = 1) solution for diffusion bonded joints

Rys. 8. Krzywe polaryzacji wykonane w 0.5 M Na_2SO_4 (pH = 1) dla połączeń z dyfuzyjnych

The obtained polarization curves for the tested joints are very similar. Their corrosion potential is within the range of –0.376 to –0.378 V. The corrosion currents were estimated to be as follow: for joints with Al, 0.14536 mA/cm^2; with Cu, 0.13852 mA/cm^2; and, with Ni, 0.16254 mA/cm^2. The lowest corrosion current was observed for the sample bonded by the copper interlayer. According to the literature studies [**L. 19–22**], such a result indicates that this joint has the highest corrosion resistance among investigates diffusion boned joints. However, Lee et al. [**L. 19, 20**] reported that Ag and alloy fillers have higher resistance to corrosion.

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 results show, that 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 the friction coefficient (0.69) and weight loss (5.3 mg) were noted for joints prepared by nickel interlayer. This 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 aluminium 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 the copper interlayer starts to crumbled during the friction test and particles 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 aluminium spacer. This could indicate that the diffusion bonded joints between titanium and stainless steel obtained by an aluminium interlayer have the best exploitation properties among investigated joints. The corrosion tests show that the copper as an interlayer is the most appropriate metal among tested materials for joining titanium with stainless steel in corrosive environment. However, the obtained polarization curves for the tested joints are very similar.

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