JOINING OF TITANIUM TO CARBON STEEL BY DIFFUSION BONDING USING DIFFERENT FILLER METALS

KONIECZNY Marek, ZAJĄC Dawid, MUSIAŁ Emil, JASIŃSKI Karol

Kielce University of Technology, Faculty of Mechatronics and Mechanical Engineering, Kielce, Poland, EU
mkon@tu.kielce.pl

Abstract

Microstructure and properties of joints of titanium and C45 non-alloy quality steel performed using aluminum, copper and nickel foils as interlayers were evaluated in the study. The process was carried out in vacuum in the temperature 600, 900 and 950 °C for 60 min for Al, Cu and Ni filler metals, respectively. The effect of used filler metal on the joints microstructure, composition, hardness and tensile properties were analyzed by means of optical and scanning electron microscopy (SEM), electron probe microanalyses and mechanical tests. When aluminum was used as a filler metal $FeAl_2$, Fe_2Al_5, $FeAl_3$, $TiAl_3$, $TiAl_2$ and TiAl intermetallic phases were formed. When copper was used as a filler metal, the phases present in joint were: Fe_2Ti, FeTi, Cu_3Ti_2, Cu_4Ti_3, CuTi and $CuTi_2$ containing additionally small amounts of Fe. When nickel was used as a filler metal at the steel/nickel interface Fe_2Ti and FeTi were formed due to diffusion of Ti through nickel layer. At the nickel/titanium interface, the layer of $NiTi_2$ was observed and the irregular shaped particles of Ni_3Ti. The maximum hardness values in the range of HV 506 to 870 were achieved at the steel/aluminum interface due to the presence of the Fe_2Al_5 and $FeAl_3$ intermetallic phases. The maximum hardness values at the metal/titanium interface were achieved for nickel filler metal due to the presence of the $NiTi_2$ and Ni_3Ti intermetallic phases and they were in the range of HV 380 to 480. The maximum bond tensile strength was obtained for copper filler metal and averagely was 245 MPa, with 4.2% elongation.

Keywords: Titanium, carbon steel, microstructure, mechanical properties

1. INTRODUCTION

Titanium is fairly expensive metal but has good erosion and corrosion resistance and very high specific strength. It led to an interest in joining titanium to steel for many practical applications [1-3]. The solubility of iron in alpha titanium at room temperature is very low therefore welding of titanium and steel is very difficult. When titanium is welded with steel the brittle intermetallic phases such as FeTi and Fe_2Ti form near the interface. Regrettably they prevent the production of technically usable welds [4]. Other method to achieve strong joints of titanium to steel is brazing since it involves melting of the filler metal only. It may eliminate problems that occur when dissimilar metals are joined. In order to braze titanium many different pure filler metals can be used and also copper base alloys, titanium base alloys and silver base alloys [5, 6]. To avoid the intrusion of detrimental impurities such oxygen and nitrogen, it is mandatory to braze titanium in vacuum [7]. Unfortunately, such reactive metal as titanium reacts easily with liquid filler materials and forms intermetallic phases that are located as continuous layers on braze boundaries [1]. Very useful 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 [8, 9]. Unfortunately also joints produced by direct diffusion bonding between titanium and steel show the formation of brittle FeTi, Fe_2Ti and Fe_2Ti_4O phases in the diffusion interface [2, 3]. It seems that the effective way to obtain strong joints of titanium to steel is diffusion bonding with an appropriate filler metal. Aluminum, copper and nickel are good candidates. They have a low price and their melting points are lower with respect to joined metals. As reported He et al. [10], titanium and stainless steel can be successfully diffusion bonded with an aluminum alloy interlayer in the temperature range from 350 to 600 °C. The benefit of the diffusion bonding using copper relies on the fact that through proper process optimization it is possible to prevent the formation of the injurious eutectoid layer that is brittle and could degrade properties [11]. In the present work, non-alloy quality steel and titanium rods were joined by diffusion bonding with the use of aluminum, copper and nickel as interlayers. The microstructure and mechanical properties of obtained joints were evaluated.

2. EXPERIMENTAL PROCEDURE

Cylindrical Grade 2 titanium and C45 non-alloy quality steel rods both having 8 mm diameter were cut into 30-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

Materials	Chemical compositoion (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	-
C45	bal.	-	0.43	0.28	0.14	0.75	0.35	-	0.12	0.053	-	0.06
	Yield strength (MPa)				UTS (MPa)				Elongation (%)			
Titanium	350				420				38			
C45	302				572				15			

The joining surfaces of the cylinders were prepared by conventional techniques using several stages of grinding papers and polished on 1 μm diamond suspension. The aluminum, copper and nickel foils of 0.1 mm thickness (99.95 % Al, 99.99 % Cu and 99.91 % Ni) were used as intermediate metals. Both surfaces of the foils were polished on diamond suspension and then there were cut circular profiles having 8 mm diameter. The carbon steel cylinders, copper and nickel foils were etched in an aqueous 5% solution of HNO_3, while the titanium cylinders and aluminum foil in an aqueous 2% solution of HF. All specimens were cleaned in acetone and dried rapidly in air. The joined titanium and carbon steel cylinders with inserted interlayers were kept in contact in a steel clamp. After that the samples together with the fixture were placed into a vacuum furnace. The compressive stress of 2 MPa along the longitudinal direction was applied at room temperature using a specially constructed piston installed in the vacuum furnace to obtain good initial contact between titanium, steel and filler metals. The diffusion bonding using aluminum, copper and nickel foils was carried out for 60 minutes in 10^{-3} Pa vacuum at 600, 900 and 950 °C, respectively. The specimens after diffusion bonding were cut longitudinally, mounted in a cold setting resin, mechanically prepared initially with a grade 1000 abrasive paper and finally using Struers polishing machine and 1 μm diamond suspension. Microstructural observations were performed using a JEOL JMS-5400 scanning electron microscope (SEM) and a Nikon ECLIPSE MA 200 optical microscope. Before the samples were examined with the optical microscope they had been etched. The titanium side and intermetallics containing aluminum or nickel were etched in an aqueous solution of 88 ml H_2O, 8 ml HNO_3 and 4 ml HF. The carbon steel side was etched by a solution containing 2 ml HNO_3 and 100 ml C_2H_5OH. A mixture containing 20 g CrO_3, 75 ml H_2O, and 5 ml HNO_3 was used for etching intermetallics comprising copper. The chemical compositions of the phases were determined in atomic percent using an electron probe microanalyser Oxford Instruments ISIS-300. Composition of the phases was ascertained by comparing the results of the microprobe analysis with the data in the ternary Al-Ti-Fe, Cu-Ti-Fe and Ni-Ti-Fe phase diagrams [12-14]. The microhardness along the cross-section of the diffusion bonded joints was performed by a Matsuzawa MMT tester under load of 0.981 N with a testing time of 15 s. Tensile strength of the bonded joints was evaluated at room temperature using an AMSLER screw machine at a crosshead speed of 0.5 mm·min^{-1}. The reported mechanical properties of the investigated joints are average values of three specimens that were tested at each processing parameter.

3. RESULTS AND DISCUSSION

3.1. Effect of used filler metal on joints microstructure and composition

Microstructural examinations showed that titanium and carbon steel join independently which of the filler metal was used. They join through the formation of interface layers between steel/aluminum, steel/copper or steel/nickel on one side and aluminum/titanium, copper/titanium or nickel/titanium on the other side, respectively, as a result of the diffusion of metallic elements. The example cross-sections of the joints are shown in **Figure 1**.

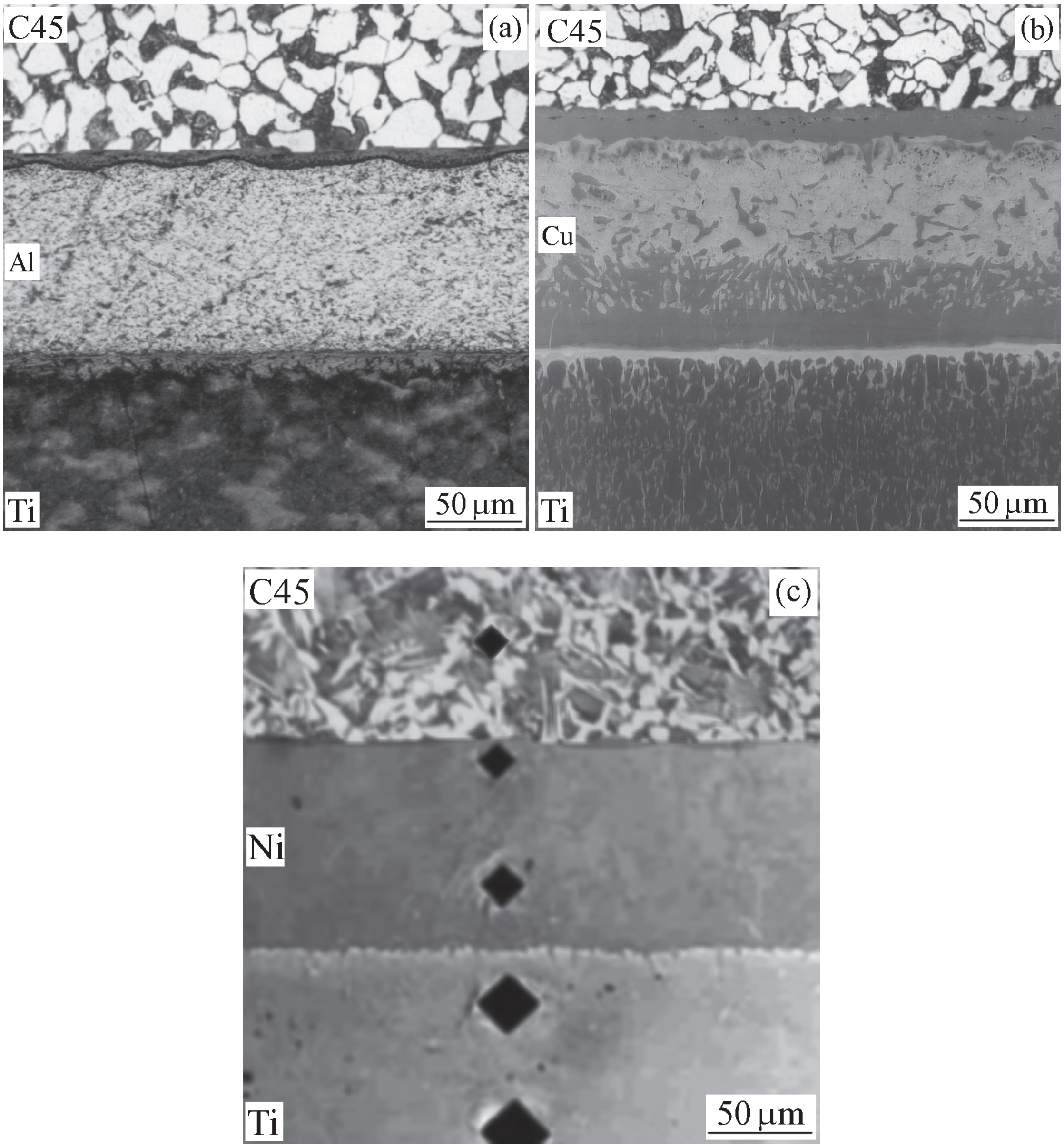

Figure 1 Optical micrographs of the joints prepared using (a) aluminum, (b) copper and (c) nickel fillers

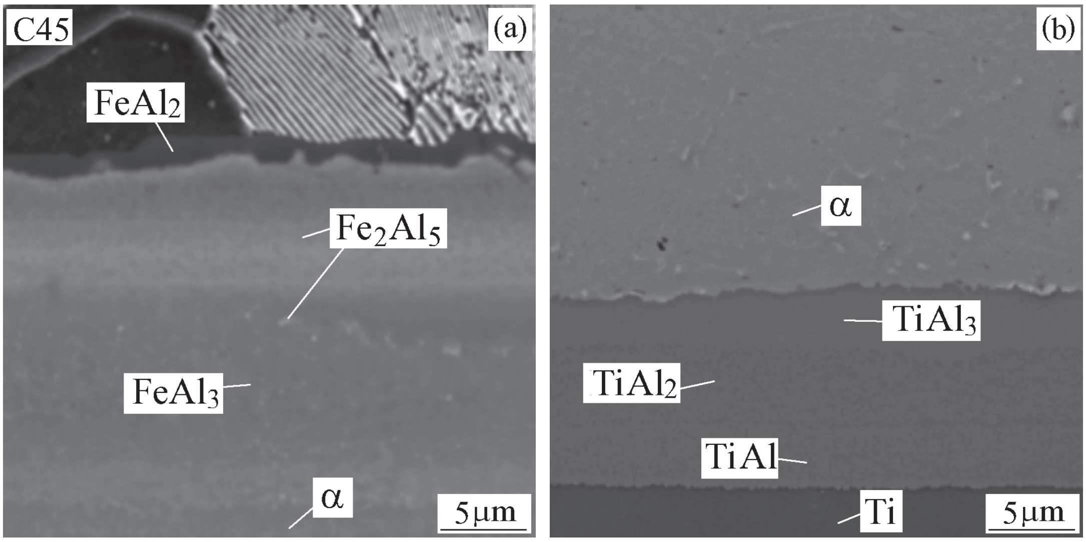

Figure 2 SEM images of the (a) steel/aluminum, (b) aluminum/titanium interface

According to the chemical analyses and the Al-Fe-Ti ternary phase diagram [12], it can be assumed that the phases present in the form of layers at the steel/aluminum interface are $FeAl_2$ (65.14 at.% Al and 34.86 at.% Fe), Fe_2Al_5 (72.44 at.% Al and 27.56 at.% Fe) and $FeAl_3$ (75.19 at.% Al and 24.81 at.% Fe) (**Figure 2a**). At the aluminum/titanium interface, the thin layers of $TiAl_3$ (74.22 at. % Al and 25.78 at.% Ti) , $TiAl_2$ (67.25 at.% Al and 32.75 at.% Ti) and TiAl (52.13 at. % Al and 47.87 at.% Ti) have been identified (**Figure 2b**). The results of chemical analyses (0.63 at.% Fe and 0.27 at.% Ti) shown that central region of joints contains only the solid solution of iron and titanium in aluminum (α).

Chemical analyses and the Cu-Ti-Fe ternary phase diagram [13] suggest that the phases present at the steel/copper interface are Fe_2Ti (31.24 at.% Ti, 65.47 at.% Fe and 3.29 at.% Cu) and FeTi (45.57 at.% Ti, 47.21 at.% Fe and 7.22 at.% Cu) with an amount of Cu admixture (**Figure 3a**). The phases present at the copper/titanium interface are Cu_3Ti_2 (40.02 at.% Ti, 2.14 at.% Fe and 57.84 at.% Cu), Cu_4Ti_3 (42.91 at.% Ti, 1.34 at.% Fe and 55.75 at.% Cu), CuTi (49.56 at.% Ti, 0.78 at.% Fe and 49.66 at.% Cu) and $CuTi_2$ (66.17 at.% Ti, 0.25 at.% Fe and 33.58 at.% Cu) containing additionally small amounts of Fe (**Figure 3b**). The phases present in the middle of joints are mostly Cu-Ti-based intermetallics and solid solutions based on copper.

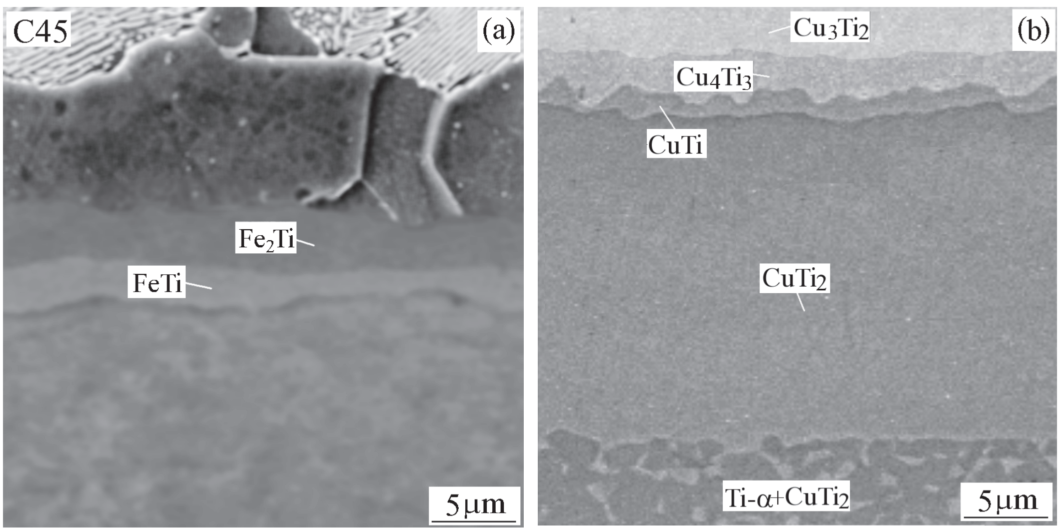

Figure 3 SEM images of the (a) steel/copper, (b) copper/titanium interface

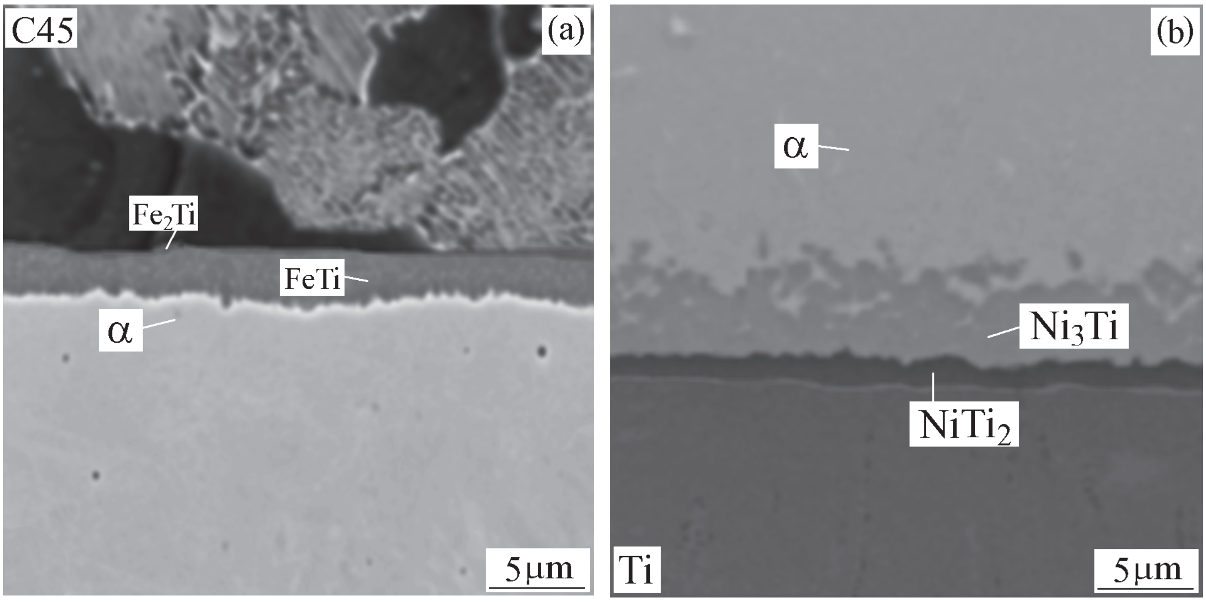

Figure 4 SEM images of the (a) steel/nickel, (b) nickel/titanium interface

According to the chemical analyses and the Ni-Fe-Ti ternary phase diagram [14], it was identified that the phases present in the form of layers at the steel/nickel interface are Fe_2Ti (32.25 at.% Ti, 64.17 at.% Fe and 3.58 at.% Ni) and FeTi (49.35 at.% Ti, 48.74 at.% Fe and 1.91 at.% Ni) with an amount of Ni admixture (**Figure 4a**). At the nickel/titanium interface, the thin layer of $NiTi_2$ (67.41 at.% Ti and 32.59 at.% Ni) has been observed. Additionally the irregular shaped particles of Ni_3Ti (24.96 at.% Ti and 75.04 at.% Ni) have been noticed in Ni-based solid solution (α) matrix (5.14 at.% Ti, 7.28 at.% Fe and 87.58 at.% Ni) (**Figure 4b**).

3.2. Effect of used filler metal on hardness of bonded joints

Results of hardness measurements performed for all obtained joints are given in **Table 2**.

Table 2 Results of hardness HV measurements under 0.981 N loading

Filler metal	Steel/metal interface	Middle of the joint	Metal/titanium interface
Aluminum	506-870	28-44	210-230
Copper	450-580	125-180	270-330
Nickel	430-510	145-160	380-480

The maximum hardness values in the range of HV 506 to 870 were achieved at the steel/aluminum interface due to the presence of the Fe_2Al_5 and $FeAl_3$ intermetallic phases. The maximum hardness values at the metal/titanium interface were achieved for nickel filler metal due to the presence of the $NiTi_2$ and Ni_3Ti intermetallic phases and they were in the range of HV 380 to 480. The minimum hardness values in the middle of the joints were achieved for aluminum filler metal. They were in the range of HV 28 to 44. In comparison, the values of hardness for used carbon steel and titanium were HV 120-370 and HV 115, respectively.

3.3. Effect of used filler metal on tensile properties of bonded joints

The room temperature tensile properties of the diffusion bonded joints with the change in bonding filler metal are shown in **Table 3**.

Table 3 Tensile properties of the diffusion bonded joints performed using different filler metals

Filler metal	Tensile strength (MPa)	Fracture elongation (%)
Aluminum	105	5.6
Copper	245	4.2
Nickel	165	4.6

The maximum bond tensile strength was obtained for copper filler metal and averagely was 245 MPa, with 4.2% elongation. According to Eroglu et al. [15] the Cu-Ti base intermetallic phases have higher plasticity than Fe-Ti and Fe-Al base intermetallics and are less detrimental to properties of joints. On the other hand, at the higher temperatures the mass transfer of the alloying elements across the interface encourages sudden increase in the volume fraction of brittle reaction products. The lowest tensile strength obtained for aluminum can be explained by the fact that not all aluminum converted into intermetallics. The tensile strength of the joint was as the matter of fact the tensile strength of the remaining aluminum. The fracture surface of the specimen joined using aluminum was featureless with the presence of voids. Fracture surfaces for specimens joined using copper and nickel was brittle with existence of cleavage pattern and discontinuities. As reported Iijima et al. [16] this could be explained owning to the fast diffusion rate of Ti in comparison to Cu and Ni. Titanium atoms moves faster across the interface, which creates imbalance in flux transfer, and therefore discontinuities are formed in the reaction zone. The considerable body of work devoted to the mechanical behavior aspects, mechanisms of damage evolution and fracture behavior of the titanium/stainless steel joints have been carried out by Szwed et al. [17].

4. CONCLUSION

1) Diffusion bonding of titanium to C45 non-alloy quality steel using aluminum, copper or nickel foils as interlayers can be properly carried out resulting in joints with good repeatable quality.
2) When aluminum is used as a filler metal at the steel/aluminum interface $FeAl_2$, Fe_2Al_5 and $FeAl_3$ are formed in the form of layers and at the aluminum/titanium interface, the thin layers of $TiAl_3$, $TiAl_2$ and TiAl can be identified. The central region of joints contains the solid solution of iron and titanium in aluminum.
3) When copper is used as a filler metal at the steel/copper interface Fe_2Ti and FeTi with an amount of Cu admixture and at the copper/titanium interface layers of Cu_3Ti_2, Cu_4Ti_3, CuTi and $CuTi_2$ containing additionally small amounts of Fe are formed. The phases present in the middle of joints are mostly Cu-Ti-based intermetallics and solid solutions based on copper.
4) When nickel is used as a filler metal at the steel/nickel interface Fe_2Ti and FeTi with an amount of Ni admixture are formed. At the nickel/titanium interface, the thin layer of $NiTi_2$ can be observed with the irregular shaped particles of Ni_3Ti. The central region of joints contains nickel-based solid solution.
5) The maximum hardness values in the range of 506 to 870 HV are at the steel/aluminum interface due to the presence of the hard Fe_2Al_5 and $FeAl_3$ intermetallic phases. The maximum hardness values at the metal/titanium interface were achieved for nickel filler metal due to the presence of the $NiTi_2$ and Ni_3Ti intermetallic phases and they are in the range of 380 to 480 HV.
6) The maximum tensile strength of the joint is for copper filler metal and averagely is 245 MPa, with 4.2% elongation.

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