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Properties of friction welding titanium-stainless steel joints with a nickel interlayer

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Abstract

The probability and appropriate processing parameters of friction welding method of commercially pure titanium to a 304L stainless steel with an electroplated nickel interlayer have been investigated. The microstructure of the welded joints has been observed by optical microscopy, scanning electron microscopy and energy dispersive X-ray spectroscopy, and the main factors affecting friction welding process were analysed. Metallographic analysis revealed that a good bonding was obtained at both the titanium/nickel and nickel/stainless steel interfaces, and the diffusion products were identified in the weld zone. The effect of friction time and forging pressure on metallurgical and mechanical properties were evaluated. The results showed that atom diffused well and no presence of Fe–Ti intermetallic compounds appeared at optimum parameters. With the increment of friction time, the thermal degradation region increasing hence the thickness of interlayer material is decreasing. Microhardness test across the joining interfaces demonstrated the effect of solid solution hardening in the weld zone. The tensile strength increased with increasing forging pressure at constant friction time. Tensile test showed that the maximum average tensile strength of ~289 MPa was obtained for the joint welded at forging pressure of 320 MPa. The tensile fracture surfaces are indicating river patterns of brittle mode of failure of the joints. The tensile fracture of the welded joint occurred in titanium side near the interface.

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Keywords: Friction welding; titanium; 304 stainless steel; nickel interlayer; microstructure, mechanical properties.

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1. Introduction

In recent years, dissimilar metals joining plays a critical role in advanced manufacturing technology, since different properties are essential with in any precise application, the properties of which cannot be attained by a solitary material. The combinations of dissimilar material joints are employed in several industrial applications, particularly in the chemical, aerospace and nuclear industries, Yanbin et al. (2010). Dissimilar materials via magnesium to aluminium and its alloys are employed in many industries since they are lightweight due to that, they are achieved a great importance as a structural materials with excellent performance and high efficiency. Steels are one of the reliable high strength and cost efficiency structural materials. Hence, it is necessary to develop dissimilar welding processes to join aluminium or magnesium to structural steels. The literature reported on joining of dissimilar materials such as aluminium and its alloys to steels, but there are very few studies are reported between titanium and steels dissimilar joints. Titanium and its alloys have high specific strength and toughness, high melting point, excellent corrosion resistance and low density, thus they have been widely used in petro chemical, cryogenic and aerospace industries, Muralimohan et al. (2014) or Fuji et al. (1992). However, with increased use of titanium and its alloys are confined by their higher price. For instance a result of this, it is necessary produce joints between titanium alloys and structural steels.

The joining of titanium to steels by using conventional fusion welding techniques is resulted in major metallurgical problems. At the weld interface Ti and Fe are not completely soluble in solid state due that the formations of brittle intermetallic compounds like FeTi and Fe_2Ti, stress concentration and segregation of chemical species, He et al. (1999). Sun et al. (1996) studied on dissimilar metal joints by conventional arc welding processes reported that the joints between Ti and Steels unsuccessful due to involve in melting of base materials. The melting and solidification of the base materials are consequences in distortion on weld shapes and effect of coefficient of linear expansion for generation of strain at weld interface. Thus, solid state welding processes such as diffusion bonding Ghosh et al. (2003), explosive welding Mousavi et al. (2009), friction stir welding Fazel et al. (2010) and friction welding Futamata et al (1990) have the lower joining temperatures and that minimize the extent of intermixing are generally used for joining steels to titanium and many such dissimilar metal combinations. Shanmugarajan et al. (2012) and Wang et al. (2010) reported that the high energy beam welding processes such as laser beam welding and electron beam welding are reducing the effect of temperature and defeating the mixer of each material respectively. Among the joints produced by solid state welding processes and high energy beam welding processes, friction welding joints were found to have the efficient and highest tensile strength Mudali et al. (2003).

The continuous drive friction welding method is a solid state welding process which the required heat is generated by mechanical friction to produce a high quality welds concerning similar or dissimilar materials. Friction welding processes improves the importance of all kind equipments creating it attractive for various industrial applications. The temperature generated amongst the two samples in contact makes a condition for developing a high reliable friction welds, Rothkirch et al. (2008). The advantages of friction welds are welding temperature is below the melting point of the base materials. The other properties such as physical and metallurgical properties will not be deteriorating as like in fusion welding methods, due to the absence of filler metals and shielding gases. The sub-melting temperatures and short weld times are resulted in superior quality a welds which makes friction welding an incredible method for industrial mass production of several combinations of work materials to be joined, Fuji et al. (2005). Friction welding processes are most economical, materials saving and ability to high reproducibility, and moreover it is an environmentally clean and low energy input.

The most important parameters in friction welding are forging pressure, friction pressure, forging time, friction time and rotational speed. The parameters impacting friction welding has been deliberated antecedently, Yilbas et al. (1995). The quality of the welds determined by the appropriately set of welding parameters. The selection of welding parameters are effects the microstructural changes. If the friction time is held long, a wide diffusion zone with presence of secondary particles. For low friction pressure, short friction times and low forging pressures the weld is weak in bond and voids are commonly found. To accomplish a maximum strength, the friction time held as short as possible, while the friction pressure and forging pressures should be as high as possible Yilmaz et al. (2003). Peng et al. (2014) investigated the effect of friction time on mechanical and metallurgical properties of friction welds between Ti6Al4V and SUS321 steel. The longer friction time leads to outsized flash on the titanium side and dense brittle intermetallic phases. Fuji et al. (1992), reported that the direct joining of titanium to 304L stainless steel (304L SS) friction welds showing the intermetallics formation in weld interface due to the high rate of diffusion of titanium in stainless steel and of Fe, Cr and Ni in titanium. Diffusion bonding of titanium to austenitic stainless steel studied by Qin et al. (2006), and reported that the presence of brittle Fe-Ti intermetallic phases lowered both the tensile strength and the ductility of the welded bonds. All these brittle intermetallic phases weaken the mechanical properties of the welds; hence the use of interlayer technique has come into renown to decimate the limitations and to develop the mechanical properties. Frictions welding of titanium with austenitic stainless steel are studied comprehensively based on metallurgical features and mechanical properties and reported literature are available extensively. However, the joining of titanium to stainless steel with interlayer technique is very limited.

In accordance with the binary phase diagrams, nickel was chosen to as an interlayer material in this present investigation. The objective of the present work is to examine the mechanical and metallurgical behavior of the joints between titanium and 304L austenitic stainless steel with nickel interlayer using friction welding method. The microstructural characterizations of welds were analyzed with varying in the different process parameters and are discussed.

2. Materials and experimental procedure

The materials employed in the present experiment were titanium and 304L austenitic stainless steel rods of length and diameter were machined in the dimensions of 12 x 80 mm respectively. The X-ray fluorescence (XRF) spectroscopy analysis has made to resolute the elemental admixture of the parent materials, as shown in Table 1. The base materials were tested for the assessment of physical properties, as shown in Table 2. The continuous drive friction welding method was used to perform the friction welding joints. A KUKA continuous drive friction welding machine operated at a constant speed of 1500 rpm was considered for joining experiments. The other principle friction welding parameters such as friction time and forging pressure are varied while the friction pressure and forging time maintained at a fixed value. Parameters employed in performing the various trails are given in Table 3. The contact surfaces of titanium and stainless steel specimens were polished by using a range of emery papers and alumina cloth polishing to maintain an equal surface roughness. The interlayer material such as nickel was deposited by electroplating on the stainless steel substrates with range of 100±3 μm. The substrates were cleaned with acetone to remove the grease and enduring contaminations before performing friction welding. The welds which were made between titanium and 304L stainless steel with nickel interlayer by friction welding process, each deform resistance differs greatly, in that the titanium base metal deforms by plastic deformation during joining. The titanium rod maintained as a rotating member and stainless steel positioned in a stationary side. The produced friction welds were resulted in the physical appearance of titanium side obtained a circular flash is greater than the stainless ide.

The evaluation of joint strengths was conducted after making joints immediately performed a drop test for all the welds at various welding parameters. After completion of the welding the resulted welds are taken out from the machine and tensile specimen was prepared as per ASTM-E8 standard. The tensile strength of the resulted welds is recorded at with increase in forging pressure and increase in friction time. The metallographic techniques were applied for all the welds made by different process parameters. The welded joints were longitudinally sectioned and a piece of 20 mm length was taken from the centre of the joint. The sectioned samples were subjected to the standard metallographic procedure such as grinding and polishing techniques before applying to the etchant. The Kroll’s reagent was used to etch on titanium side. Similarly, the stainless steel side was etched using an aqua regia solution. Subsequent to etching, the microstructural studies of samples were examined by using optical microscope as well as the unetched samples were also examined using scanning electron microscope (SEM). The chemical composition of various phases formed in the weld interface was determined by energy dispersive X-ray spectroscopy analysis (EDS).

Microhardness (vickers) profile has been taken across the both substrates and nickel interlayer as well as interface of the weld was measured to evaluate a quality of the joint by variation in hardness values of friction welds. A Zwick 3212 vickers hardness tester was used to measure the vickers hardness value under a load of 300 g for 10 s duration for stainless steel and 100 g for 10 s on titanium side. Tensile testing was conducted at room temperature using a computer programmed testing machine with a cross head velocity of 0.02 mm/min. The tensile fractured surfaces were captured with SEM to observe the fracture morphology characteristics and identify the fracture location. The dispersion of chemical species across the interface of welds was measured by X-ray diffraction (XRD) analysis.

Table 1. Chemical composition of base materials (wt%).

Materials	O	H	C	N	Ni	Cr	Mn	Si	Fe	Ti
Titanium	0.18	0.015	0.08	0.03	-	-	-	-	0.03	Balance
304L stainless steel	-	-	0.05	-	10.16	18.98	1.83	0.34	Balance	-

Table 2. Mechanical properties materials used in the experiment.

Base materials	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
Titanium	437	286	36
304L stainless steel	530	235	65

Table 3. Friction welding conditions.

Forging pressure (MPa)	Friction pressure (MPa)	Friction time (s)	Forging time (s)
280-330	182	1-6	8

3. Results and discussions

3.1. Microstructural characterization

The formation of weld flash at weld interface showing changes of their physical appearance of the resulted friction welding joints held at different friction times. The amount of weld flash for different friction times is unsymmetrical and it is observed that the flash range for 6 s is much greater than that for 1 s, while the constant higher forging pressures. The weld flash mainly formed at the titanium side and the stainless steel did not participate in flash formation. From the welds it is observed that the reduction in tensile yield strength of titanium with heat is much more noteworthy than that of stainless steel, even though the yield strength of titanium at atmospheric temperature is greater than 304L stainless steel. The unetched microstructures of the titanium to stainless steel with the differences in thickness of nickel interlayer with changes in friction time are shown in Fig.1. The gradual decrease in thickness of nickel interlayer designate that interlayer had deformed through the friction welding processes. The average thickness of the nickel interlayer is decreased with increase in friction time of friction welds. The thickness of nickel interlayer reducing with increasing in friction time from 95 µm at 1 s to 56 µm at 6 s. In friction welding process the amount of heat generation at interfaces is depending on friction times, due to the results of it at higher friction times the interlayer deformed to more extent and in consequence formed a thin interlayer at the weld interface.

The microstructures of cross section of the successful friction welds between titanium and stainless steel are shown in Fig. 2. The optical microstructure of friction welds produced at forging pressure 320 MPa and friction time 6 s is shown in Fig. 2 (a); it is exhibiting a fine grain microstructure at the titanium side. That indicates the titanium deformed to a greater extent due to the frictional heat generation by rubbing two mating surfaces at the interface with the effect of forging pressure and friction time. Ti was experienced to plastic deformation at higher temperatures; hence the existed dynamic recrystallization had resulted in fine equi-axed grains close to the weld interface. The thermal conductivity of stainless steel is larger than that of titanium substrate. Thus, the formation of heat at interface by frictional effect is mainly produced on titanium side because of its low thermal conductivity temperature. However, there is no noticeable change of recrystallization effect at the stainless side. The microstructural deformation and frictional heat at the weld interfaces that has been dissipated through the base metals had resulted in a temperature gradient causing materials formed with different microstructures. Moreover, the effect of friction pressure brings the joints to plastic deformation which resembles dynamic recrystallization that leads to the grain refinement at welds interface, Ozdemir et al. (2007). The weld interface between titanium and nickel interlayer is characterized by thin transition layer revealed at the interface region. The transition layer

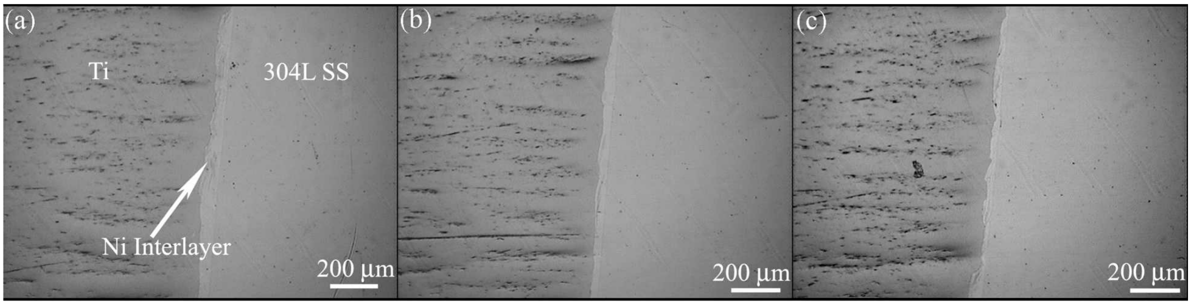

Fig. 1. The micrographs show the different interlayer thickness of joints at (a) 2 s, (b) 4 s and (c) 6 s, of the initial interlayer thickness of 100 μm.

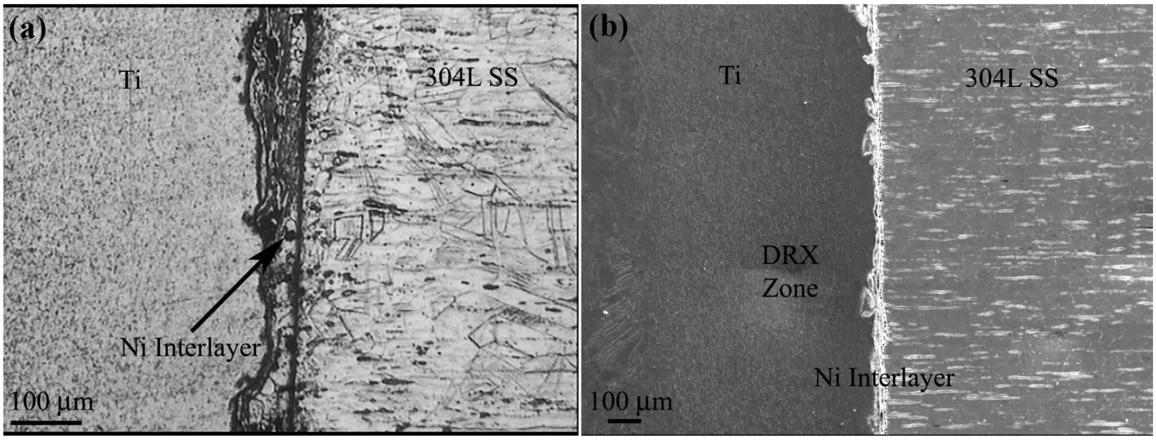

Fig. 2. Microstructures of the welds at friction time of 6 s (a) optical microscopy (b) SEM

thickness increases with increasing friction time. The linear depends of the transition layer thickness on the square root of the friction time implies that the growth of interface is caused by diffusion, Yilmaz et al. (2003). The interface between titanium and interlayer is irregular in shape whereas the interface between interlayer and stainless steel is straight and planner in nature. It indicates that the intermixing of both substrates and the migration of atoms between titanium and nickel interlayer, while the formation of welds. The microstructure on stainless steel side consists an austenite phase with twin boundary, and the transaction zone between nickel interlayer and stainless steel is smaller than that of titanium to nickel interlayer interface. SEM microstructure of the welds as depicted in Fig. 2 (b). The SEM images are showing a good bonding along the interfaces of titanium to nickel interlayer and interlayer to stainless steel. It is observed that both interfaces are free from formation of micro level weld cracks and discontinuities of bonding lines. The SEM microstructure clearly exhibits a wider region of dynamic recrystallization zone on titanium side near the weld interface.

3.2. SEM-EDS analyses

SEM-energy dispersive X-ray analysis is employed to investigate the diffusion of elements across the weld interface during welding. Fig. 3 shows the locations at which SEM-EDS spot scan analysis were taken across the friction welds and both the interface regions. The major elements of both substrates and nickel interlayer had inter-diffused through weld interfaces, and therefore the possible combinations of intermetallic phases were formed at the two weld diffusion lines. The composition of the chemical species was determined at the two bond lines. The EDS

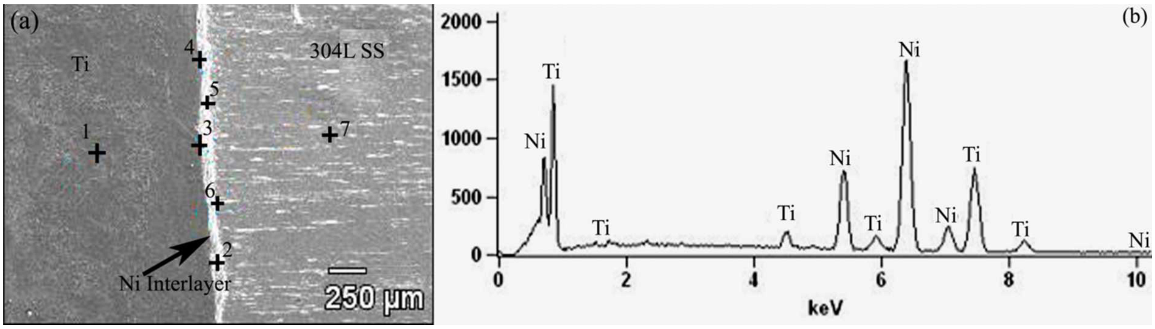

Fig. 3. EDS spot scan analysis of the welds (a) SEM image showing the different scan points (b) EDS analysis at point 2.

spot scan spectrum (point 2) at the interface between titanium and nickel interlayer is shown in Fig. 3 (a). In the mutual transition layer at nickel interlayer to titanium interface, the presence of elemental composition changesgradually for Ni and Ti. The presence of existed values of the composition of chemical species at, nickel side (point 2) is Ni (~78.4–81.9 at.%) and Ti (bal) and corresponds to $TiNi_3$ intermetallic compound, Hinotani et al. (1988) and Cheepu et al. (2012).. The presence of chemical composition of the interface near to the titanium side (point 3) is enriched with the Ti (~57.4–61.8 at.%) and the Ni (bal) is correspond to the formation of $NiTi_2$ intermetallic phases, He et al. (1999). The average composition of the EDS spectrum of point 4, at the interface of titanium and nickel interlayer is Ti (~49.5–52.3 at.%) and Ni (~44.7–50.8 at.%). According to the Ti-Ni binary phase diagram this is a TiNi intermetallic compound layer. The interface of nickel to stainless steel characterized to identify the possible to formation of intermetallic phases of combination of Fe, Ni and Cr. EDS spot scan spectrum of point 5 at interface the presence of Fe (~12.5–16.2 at.%) and Cr (~1.2–2.9 at.%) in the nickel side designates the significant dispersion of two alloying elements. The presence of Ni (~24.8–46.9 at.%) at point 6 in the stainless steel side designates the migration of nickel into stainless steel side. The small quantity of nickel concentration is enough to form any kind of nickel base intermetallic phases; therefore, disregarding the effect of nickel, the Fe-Cr-Ni ternary phase diagram suggests that the possibility to formation of $Fe+\lambda+\chi$, Raghavan (1987) and Kundu et al. (2004). Therefore, the formation of intermetallics effects the degradation of tensile strength of the welds.

3.3. Microhardness distribution

The micro hardness measurements were made across the welds to identify the microstructural strength on heat affected zone, base metals, interlayer material and both interfaces are shown in Fig. 4. The hardness profile gradually increasing from the substrates to the respective weld interfaces. Virtually the similar tendency of hardness distribution is identified for the two welded materials are considerably increases in the dynamic crystallization zone and the highest hardness value is attained near the weld interfaces. This is due to the grain size in dynamic crystallization zone is finer than that of heat affected zone, so the dynamic crystallization zone has a higher hardness value rendering to the Hall-Petch relationship, Sato et al., (2003). It is observed that the hardness profile in Fig. 4 showing a steep increase in hardness in titanium side near the weld interface is directly related to the microstructure formed in the welds as a result of strain hardening effect during the friction welding process, Seli et al. (2010) and Muralimohan et al. (2013). However, the increase in hardness at stainless steel side is very less compared to titanium side it is indicating that the strain hardening effect is less and the extent of deformation of limited in stainless steel compared to titanium. Based on the distribution of hardness profile it can be declared that the hardness values of the combination of intermetallic compounds were newly generated in the welds has higher value than that of substrates. The highest hardness recorded at titanium/nickel interface can be attributed to the formation of intermetallics of titanium and nickel. All the above discussed factors can together impact and result in the hardness profile may directed that the weld interface is the weakest region when experienced to load. The formation Ni/Ti intermetallics at weld interface are cause to the degradation of weld strength of the joints.

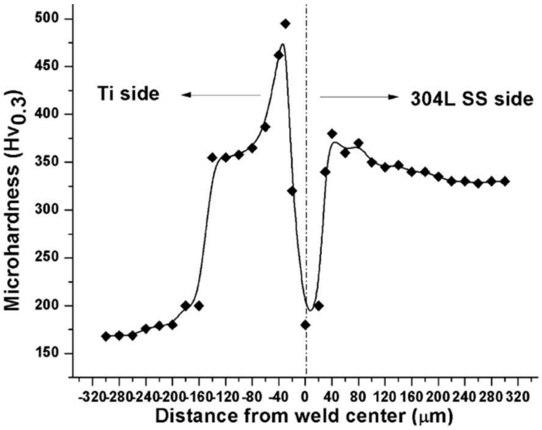

Fig. 4. Microhardness distribution across the joints

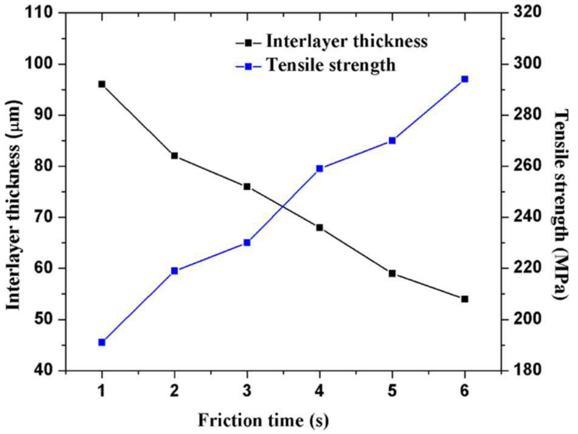

Fig. 5. The effect of friction time on tensile strength and interlayer thickness

3.4. Tensile properties

Tensile tests were performed to evaluate the fracture strength of the joints and location of weak part in the joints. The variation of average tensile strength of the welds as a function of friction time is presented in Fig. 5. The result of the tensile tests shows that the average tensile strength of the friction welds increases as the increases in friction time. In the present investigation the maximum average tensile strength of 289±6 MPa is exhibited by the joint produced with the friction time of 6 s and forging pressure of 320 MPa. In the interim, the thickness of the nickel interlayer after the joint was produced with titanium and stainless steel is decreased with the increase in friction time. The thickness of interlayer at the highest tensile strength was resulted that the 60±5 µm. The results of longer friction times that formed an excessive generated heat and it makes the nickel interlayer deformed to a larger account and which makes the substrates to form a welding and interlocking with weld interfaces. Hence, the completion of friction welding process, the thickness of interlayer material between the two substrates was found to decrease through the further rising of friction times. Subsequently the lower period of friction times, are not able to generate the required temperature to diffuse the nickel interlayer. It can cause to the thickness of interlayer becoming thicker and detrimental to the tensile strength of the joints. It is clearly indicating that the tensile strengths of the friction welds depended on the nickel interlayer thickness. Whereas, incomplete to providing a plasticity process also happened owing to the lower friction times, Mohamad et al. (2008). The tensile strength of welded joint also increased slightly with increase in forging pressure over the 280 MPa is shown in Fig. 6. Whereas the amount of upset increased constantly with increasing forging pressure, in this regard forging pressure of 280 MPa does not contribute to increasing the tensile strength regardless of friction time. Therefore, the average weld strength is attained at a friction time of 6 s and forging pressure of 320 MPa. Though, all the joints tensile fracture occurred at titanium side on titanium and nickel interface.

3.5. X-ray diffraction analysis

The XRD patterns of the tensile fractured surfaces of Ti/Ni and Ni/304L SS interfaces were analyzed and the results are depicted in Fig. 7. The XRD results confirmed that the formation of new intermetallic phases on the interface of the tensile fractures. The peaks from the XRD studies are corresponding to $TiNi_3$, NiTi, Ti_2Ni, and α-Ti were detected on the fractured surfaces of the titanium and stainless steel sides respectively. Hinotani et al. (1988) and Kundu et al. (2004) have studied on Ti–Ni system and reported that the possible to form the range of intermetallics and some of them are Ni_3Ti, NiTi, Ti_2Ni, α-Ti, $Ti(Ti_{0.11}Ni_{0.89})_3$, $Ti_{33}Ni_{67}$, $Ti_{25}Ni_{75}$. However, the formation intermetallics depending different conditions and few of them form at working temperatures are higher

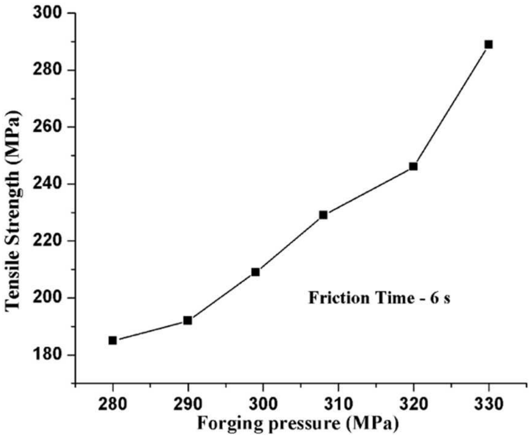

Fig. 6. Variation of tensile strength as increases with forging pressure

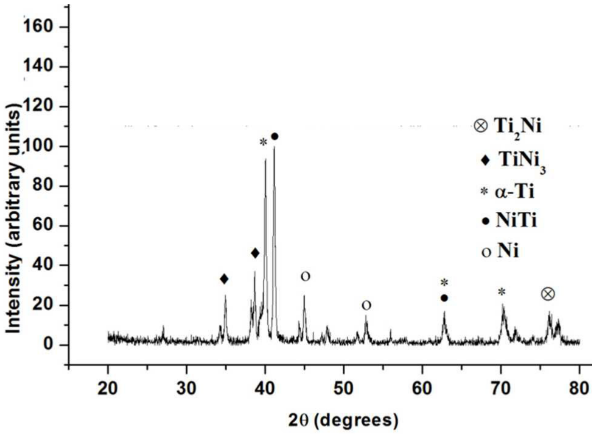

Fig. 7. XRD pattern of fractured surfaces of the joints produced with friction time of 6 s.

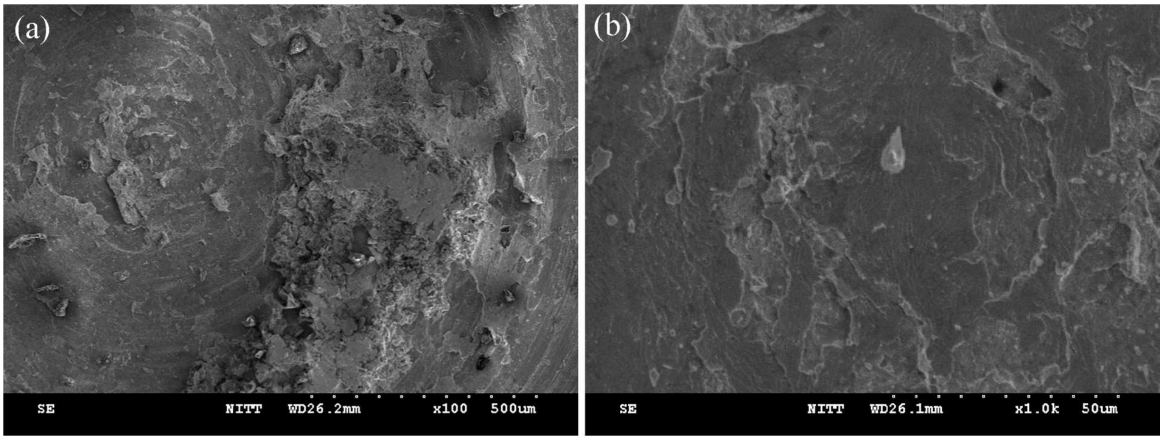

Fig. 8. SEM micrographs of the tensile fracture morphologies of titanium side welded at different friction times (a) 1 s and (b) 6 s.

than the melting point of the nickel and few have very narrow range of composition. However, the formation of a definite quantity of intermetallics phases is necessary to obtain good quality welds, while the excess amount of the presence of intermetallics at weld interface reduces the weld strength to beneath original values Fukumoto et al. (1997). The XRD results also confirmed that the formations of highly brittle Fe–Ti intermetallic compounds are successfully avoided by introducing the nickel interlayer. Whereas, the formation of intermetallics between nickel and titanium are not avoided and these intermetallics are plastic in nature and less impact on strength of the joints as compared to Fe-Ti or Cr-Ti intermetallics. The XRD results showing that tensile fracture at the Ti/Ni interface is due to the formation of Ti–Ni intermetallic compounds.

3.6. Fracture morphology

The morphology of the fracture of the joints produced at the friction times of 1 s and 6 s and the forging pressure of 320 MPa are shown in Fig. 8. The failures that seemed to have taken place in the nickel interlayer left a small amount of nickel layer on fracture surface of the both substrates. The fracture surfaces of the joints produced at the friction time of 1 s, of the titanium substrates showed a general tendency for separation of interfaces; mainly at the center part of the substrate where the weld strength is usually in weak is depicted in Fig. 8 (a). From the fracture surfaces it is observed that at shorter friction time conditions the fractured surfaces are relatively rough as compared to longer fiction times. It can be seen that owed to the inadequate heat developed at the welds during the joining method, the nickel interlayer contact with two connecting surfaces of the substrates is insufficient. Sassani et al. (1988) showed the presence of interlayer foil on fracture surfaces and reported that the portion of the interlayer material is detaching on the surfaces of the substrates due to deficient plasticization of materials. At higher magnifications the fracture morphology reveals that the presences of the region of dimples are microscopic indication of tensile fracture in the nickel interlayer material is depicted in Fig. 8 (b). The fracture morphologies of joints as the friction time increases from 1 s to 6 s the fracture surfaces were changing in physical appearance of rough surface characteristics to flat wavy surfaces, which results in the constant bonding interface is attained, conforming to the higher strength of the friction welds. It can be confirmed that the fracture morphologies are related to brittle nature of fracture which can be clearly seen as river patterns on fracture surfaces at longer friction times.

4. Conclusions

In this present work, studies on friction welding of titanium and 304L stainless steel with the introduction of nickel interlayer joints having different microstructural and mechanical properties have been carried out. The effect of experimental conditions and results of which on metallurgical and mechanical properties evaluation are drawn in the following conclusions:

- The welds were carried out at different friction times and its shows a typical unsymmetrical appearance of the joints. The nickel interlayer thickness decreasing with as increase in friction time (1 – 6 s).
- The highest joint strength of 289±6 MPa was achieved at friction time of 6 s. The strength of the welds increasing with longer friction times. Although, the higher friction times leads to the formation of thick intermetallics at interface and forming a large amount of flash on titanium side.
- XRD and EDS studies were detected the formation of intermetallic compounds of $TiNi_3$, NiTi and Ti_2Ni on the fracture surfaces and weld interfaces respectively.
- The interface between Ti and Ni was indicated the presence of highest hardness value and the hardness profile gradually increasing from the substrates to the respective weld interfaces.
- The tensile fracture surfaces were observed the river patterns morphology and indicate a brittle mode of fracture.

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