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Friction welding of titanium to 304 stainless steel with electroplated nickel interlayer

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Abstract: Friction welding is a solid state joining process and it is best suited for joining dissimilar metals. It overcomes the problems associated with the conventional fusion welding processes. The joining of dissimilar metals using fusion welding processes produce brittle intermetallic precipitates at the interface which reduce the mechanical strength. Various aerospace, nuclear, chemical and cryogenic applications demand joints between titanium and stainless steel. Direct joining of these metals results in brittle intermetallics like FeTi and Fe_xTi_y, at the weld interface, which is to be avoided in order to achieve improved properties of the joints. Present study involves joining of two industrially important dissimilar metals such as commercially pure titanium and 304 stainless steel by friction welding with electroplated nickel coating as interlayer that can prevent the brittle intermetallic formation. Microstructural details of the interfaces of the friction welded joints were studied by optical microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) technique and X-ray diffraction (XRD). Microhardness survey was carried out across the joints and tensile test was conducted to assess the mechanical properties of the joints. Fractography studies were carried out on the fracture surfaces of the joints to know the region of failure as well as the mode of failure. XRD patterns indicate the presence of intermetallics in the friction welded joints. These two metals were successfully joined by having electroplated nickel as interlayer. The weld interface on titanium side contained Ti-Ni intermetallics layers, in which the hardness of the weld metal showing the higher value than the base metals. Fractography study conducted on the fracture surfaces created due to pull test reveals that the failure is by brittle fracture and occurred at the intermetallics layer. The maximum strength of the joints achieved for 30 μm and 50 μm thick electroplated nickel interlayers are 242 MPa and 308 MPa, respectively.

Introduction

Titanium and its alloys have high specific strength and toughness, low density, high melting point and excellent corrosion resistance for medium temperature applications. All these properties increased the use of Ti and its alloys. Some applications demand the joints made between Ti alloys and structural steels. Especially, dissimilar joints between Ti and austenitic stainless steels are being widely used in aerospace, nuclear, and chemical industries [1,2]. Traditional fusion welding processes which involve melting of base materials have proved unsuccessful in joining stainless steels to titanium [3] because of the formation of brittle intermetallics, segregation of chemical species and stress concentrations in the weld metal, which result in embrittlement of joints. Attempts made for direct joining of titanium to stainless steel using solid state welding methods like explosive welding [4], friction welding [1] and diffusion bonding [5] have shown the formation of intermetallic compound like FeTi, Fe_2Ti and Cr_2Ti in the diffusion zone. These intermetallics make the transition joints brittle and susceptible to cracking that leads to formation defects such as micro cracks at the bond region [6]. The main reason for crack formation is the large difference in linear coefficient of thermal expansion between these materials, which results in generation of high internal stresses in the weld zone. However, all these solid state welding methods significantly improved the tensile strength when compared to fusion welding. Among the joints produced by these solid state welding methods, friction welded joints exhibited maximum tensile strength [7]. It is possible to avoid internal stresses by using a suitable insert metal as interlayer between titanium and stainless steel. During welding interlayer deforms and minimizes the thermal expansion mismatch [8] and, inhibits diffusion of undesired element so that ill effect of brittle intermetallic phases is reduced if not fully avoided [9]. Kundu et al. reported that aluminum [9] and nickel [10] can be used as interlayers to avoid Fe-Ti intermetallic phases.

Inserting interlayers in friction welding process is a difficult task compare to diffusion bonding. In diffusion bonding as the substrates are in static condition inserting of interlayer is very easy, whereas in friction welding one of the substrate is rotating at high speed, so mere physical insertion of interlayer posses difficulty in achieving quality welds. The present work aimed at studying the use of nickel interlayer in the form of electroplated coating on the faying surface of stainless steel so as to produce the joint between the Cp-titanium and 304 stainless steel with a view to identify suitable interlayer coating thickness. The choice of nickel is due essentially to its known compatibility with SS and Cp-titanium, plastic accommodation at the bonding temperature and ensuring an intimate contact between the welding interfaces [8,9]. However, the mechanical properties of the resulted welds are markedly dependent on the thickness of the Ni interlayer. So the joints produced by continuous drive friction welding between Cp-Ti and 304 SS with electroplated nickel interlayer were investigated for their microstructure and mechanical properties.

Experimental Procedures

The materials used in the present study were commercially pure titanium (Cp-Ti) and type 304 stainless steel (304 SS) in the form of rods of 16 mm diameter. The chemical composition of titanium is (wt %) Ti-0.18O-0.03Fe-0.015H-0.03N-0.08C. The mechanical properties of the titanium are: yield strength 286 MPa, tensile strength 435 MPa, and elongation 36%. The chemical composition of the 304 stainless steel is (wt %) Fe-18.15Cr-8.37Ni-0.08C-0.38Si-1.64Mn and mechanical properties are: yield strength 240 MPa, tensile strength 535 MPa, and elongation 65%. Ni interlayers were electroplated onto the 304 SS to the thickness of 30 μm and 50 μm at Titan Industries Ltd., Hosur, India. A KUKA continuous drive friction welding machine was used for producing the joints. The friction welding parameters employed are: heating pressure 160 MPa; upsetting pressure 200 MPa, heating time 6 sec, upsetting time 5 sec and rotational speed 1125 rpm. Before joining, the contacting surfaces were cleaned with acetone to remove organic contaminants such as oils, grease, etc. After welding flash was removed by machining. Tensile tests (pull test) were carried out to evaluate the mechanical properties of the joints on computerized universal testing machine. Samples for microstructural characterization and hardness testing were cut in transverse weld and prepared metallographically. 304 SS was etched electrolytically in 10% oxalic acid while titanium was etched using Kroll's reagent. Microstructural analysis across the joint interface was carried out by optical and Hitachi S-3400N scanning electron microscope (SEM). Elemental composition was evaluated by SEM-EDAX in line scan mode. Fracture surfaces were observed in SEM to investigate the failure modes of the joints. Vickers microhardness survey was carried out across the interface with a load of 500 g. Moreover, X-ray diffraction analysis was carried out by the diffractometer, in the scanning range of 20^0-80^0 with step size and time of 0.05^0 and 1sec, respectively with Cu Kα radiation to identify the phases formed on the joint fracture surfaces after having performed the tensile test on the fracture surfaces.

Results and Discussions

Microstructure and SEM-EDS analysis. Microstructures of the cross section of the Ti to 304 SS joints with Ni interlayer thickness of 30 μm and 50 μm are shown in Fig. 1. Cp-Ti deforms to a greater extent because of its lower yield strength than 304SS at elevated temperatures resulting in fine equiaxed grains on Ti side near the weld zone while not much variation is observed in grain size in stainless steel. However, on stainless steel side the direction of metal flow at the weld interface towards rotational direction can be seen. SEM microstructures of the welds are shown in Fig. 2. It clearly represents that the thickness of the interlayer remaining at the interface after welding is different for 30 µm and 50 µm Ni interlayers. During friction welding, the contact surfaces are subjected to combinations of high pressure and temperature which makes the interlayers to plastically flow and thus extruding out as flash. Thus initial thickness of the interlayer decides the residual thickness of the interlayer in the weld. Almost no interlayer is seen at the interface for 30 µm interlayer while interlayer of several microns thick remains in the weld produced with 50 µm thick interlayer.

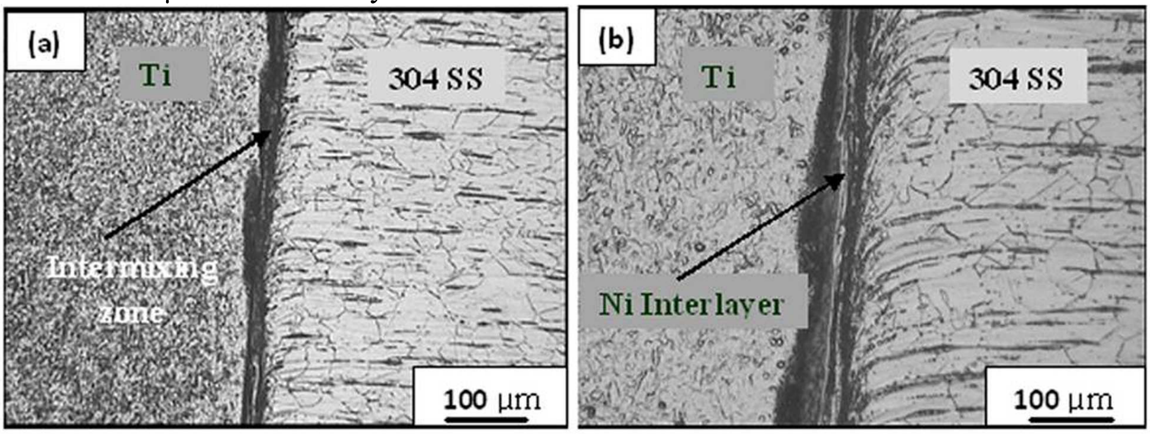

Fig. 1 Optical microstructures of the cross sections of Ti/304SS welds with Ni interlayer thickness of (a) 30 µm (b) 50 µm

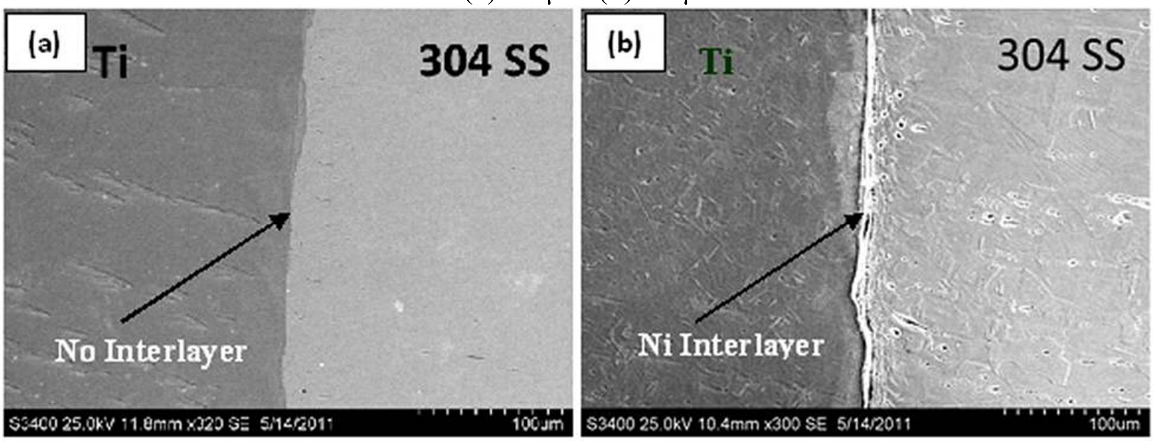

Fig. 2 SEM microstructures of the cross sections of Ti/304SS welds with Ni interlayer thickness of (a) 30 µm (b) 50 µm

Constituent elements of interlayer material and both the substrates can inter diffuse through the weld interfaces and therefore some intermetallic compounds can be formed at the Ti-Ni weld interface. A line scan EDAX profile recorded across the weld interface of the joints with 30 µm and 50 µm thickness of Ni interlayer is shown in Fig. 3. The EDAX line graphs clearly reveal the existence of an intermixed region at the weld interface with a composition between that of Ni interlayer and two base substrates such as Ti and 304 SS. There is a gradual change in the percentage of Ni at the interface on titanium side in the joint produced with 30 µm thick Ni interlayer whereas there is an abrupt change at the 304 SS interface. This variation is probably due to the higher diffusivity of Cr and Fe into Ti than the Ti into Cr and Fe [11]. Further Ni is completely expelled from the interface resulting in direct contact of the two base substrates. Due to this the intermixing of the Ti with Fe, Cr and Ni formed the secondary phases such as Ti_2Ni, $TiNi_3$, TiNi, Fe_2Ti and Cr_2Ti. Whereas for 50 µm thick Ni interlayer weld at the interface it is observed that though diffusion of Ni into Ti is possible, concentration of Ni varies abruptly indicating the presence of undissolved/uncombined nickel. It can also be seen that the intermixing zone width is wider between the Ti and Ni than at the Ni-304 SS interface. The EDAX line graph confirms the presence of Ni interlayer at the interface and no Fe-Ti intermetallic compounds are formed. The intermetallic phases formed at the Ti-Ni interface are NiTi and $TiNi_3$. There is no formation of intermetallic phases at the Ni-SS interface. Ni and 304 SS both have fcc structure and therefore so the extent of diffusion is limited at the Ni-304 SS weld interface.

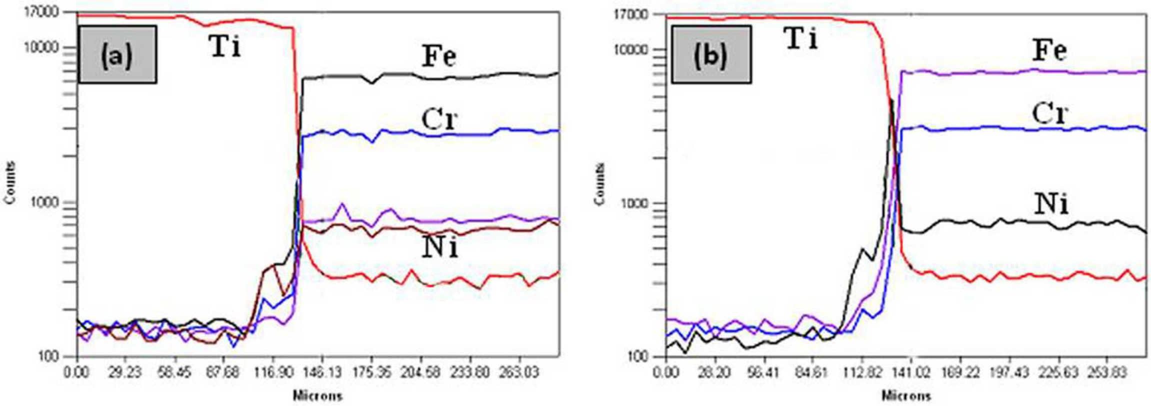

Fig. 3 SEM-EDAX line scan across the interface of Ti/Ni/304SS welds with interlayer thickness of (a) 30 µm (b) 50 µm

Mechanical Properties. The Vickers micro-hardness testing of the transverse section of the welded samples was carried out at both the weld interfaces. The hardness profiles across the cross section of the Ti/Ni/304 SS welded joints with 30 µm and 50 µm thick Ni interlayers are shown in Fig. 4. It can be seen that, the hardness increases from base metal to weld interface. The highest hardness is observed at interface of the 30 µm thick Ni interlayer joint and such a high hardness is mainly due to the formation of intermetallic phases. The gradual increasing of hardness in both substrates near to the weld interface can be attributed to strain hardening and introduction of residual stresses. Ti-Ni interface of the Ti/Ni/304 SS weld with 50 µm thick Ni interlayer joint show higher hardness than the Ni-304 SS interface. It is showing that the Ni-304 SS interface is free from formation of intermetallic phases, whereas the Ti-Ni interface contains intermetallic compounds like TiNi and $TiNi_3$. Across the Ni interlayer slight variation in hardness is observed. With electroplated Ni of thickness 30 µm and 50 µm as interlayer sound joints of Ti-304 SS are produced by friction welding. The tensile strength of the joints achieved for 30 µm and 50 µm nickel interlayers are 242 MPa and 308 MPa, respectively. Tensile strength is totally increasing with increasing the thickness of electroplated Ni interlayer. Because the 30 µm thick Ni interlayer is not sufficient for avoiding the formation of Fe-Ti phases, which, as mentioned before, represents the most harmful phase in the joint.

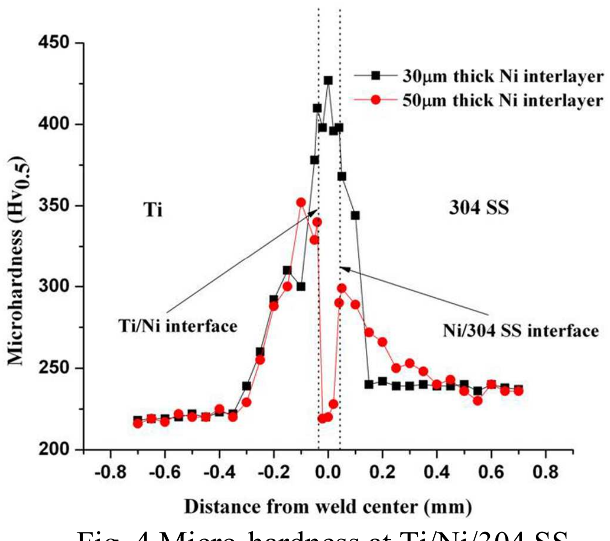

Fig. 4 Micro-hardness at Ti/Ni/304 SS interface of the welds

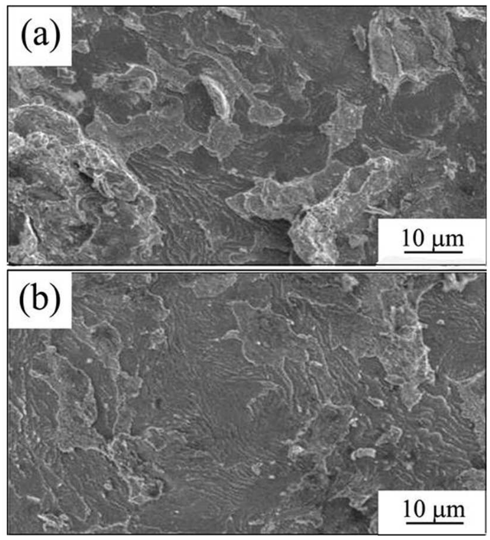

Fig. 5 Fractured surfaces of the welded joints at interlayer thickness of (a) 30 µm (b) 50 µm

Fractography. The fracture morphologies of Ti side after having performed the tensile test (pull test) are shown in Fig. 5 (a) and (b) for interlayer thickness of 30 µm and 50 µm, respectively. The fracture surface of the 30 µm interlayer weld is having the cleavage planes, faceted region and also showing the presence of ductile intermetallic phases. Whereas the fracture surface of welds with 50 µm thick interlayer is containing the facets and showing the mixture of brittle and ductile modes of failure. However, in both cases fracture took place at the interfacial region between interlayer and titanium; in the case of 30 µm interlayer the fracture was along the region where Fe-Ti intermetallics were formed and in the case of 50 µm interlayer the path was in between titanium and the interlayer material where Ti-Ni intermetallics were formed.

XRD Studies. XRD patterns from fractured surfaces of Ti and 304 SS side at 30 µm and 50 µm thick Ni interlayer welds were analyzed and the results are shown in Fig. 6. The results depict that the interface consists of Fe_2Ti, Cr_2Ti, Ti_2Ni and $TiNi_3$ on 304SS side in the 30 µm thick interlayer welds.

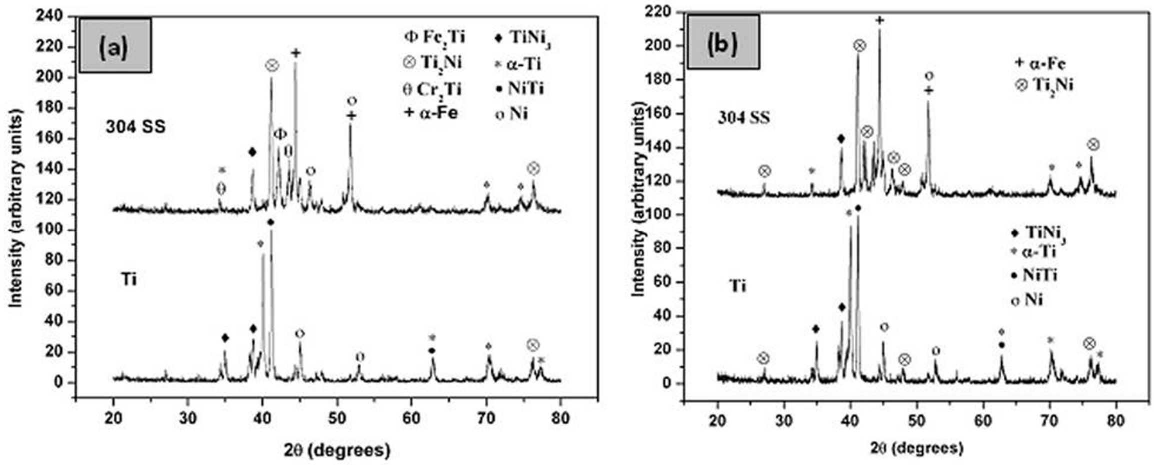

Fig. 6 X-ray diffraction analysis on fractured surfaces of Ti and 304 SS side of welds with Ni interlayer thickness of (a) 30 µm (b) 50 µm

However, peaks correspond to Ti and Fe phases were not observed on 304 SS side of the 50 µm thick interlayer welds, which denotes that the Ni interlayer completely blocked the interdiffusion and formation of Fe-Ti brittle intermetallic phases. The fractured surface of the both conditions of Ti side contains the NiTi, $TiNi_3$, and Ti_2Ni. Higher embrittling nature of Fe-Ti phases than the Ti-Ni phases is cause for reduced strength of the 30 µm thick Ni interlayer welds.

Conclusions

The solid state friction welded joints of commercially pure titanium to 304 stainless steel with interlayer of 30 µm and 50 µm thick electrodeposited nickel are produced and fracture strength of these joints are 242 MPa and 308 MPa, respectively. Interlayer of 30 µm is not sufficient to avoid the formation of Fe_2Ti and Cr_2Ti phases while 50 µm thick interlayer could completely block the intermixing of Ti and 304 SS. Therefore hardness of the interface in the 30 µm thick interlayer welds recorded the highest value. But still NiTi, $TiNi_3$ and Ti_2Ni intermetallics are formed in welds with 50µm thick interlayer. The hardness of Ti/Ni interface is higher than the Ni/304 SS interface, indicating that presence of Ti-Ni intermetallic phases at Ti/Ni interface. Fractography also reveals that presence of intermetallics is the cause for the reduction in fracture strength.

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