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Interfacial reactions and strength properties in dissimilar titanium alloy/Ni alloy/microduplex stainless steel diffusion bonded joints

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ABSTRACT

The interfacial reactions and strength properties of a titanium alloy/ microduplex stainless steel diffusion bonded joint using Ni alloy as an intermediate materials was investigated in the temperature range of 800 to 950 °C for 75 min and at 950 °C for 15–90 min in vacuum. The microstructure observations at the stainless steel/Ni alloy interface indicate the presence of γ-Fe layer up to 900 °C for 75 min and at 950 °C up to 45 min. Ni_3Ti, NiTi and $NiTi_2$ intermetallic layers were observed at the Ni alloy/titanium alloy interface at the same processing parameters and irregular shaped particles were present within the $TiNi_3$ intermetallic layer. Beyond these processing parameters, the layer wise Fe–Ti or Fe–Cr–Ti base intermetallic compounds were observed at the microduplex stainless steel/Ni alloy interface. Maximum tensile strength of ~639.9 MPa and shear strength of ~477.8 MPa along with ~9.3% ductility were obtained for the diffusion couple processed at 900 °C for 75 min.

1. Introduction

With important properties, such as high specific strength, high toughness at ambient temperature, excellent corrosion resistance for medium temperature applications and high creep resistance at elevated temperatures [1–3]. With increased use of titanium alloys in aerospace, nuclear and chemical industries, the effective utilization of titanium alloys needs the development reliable joining techniques, especially joining techniques of titanium alloys to other materials such as stainless steel which has wide application in industry [2–5]. The existing methods for joining titanium alloys to stainless steel include welding, brazing and diffusion bonding, however, the conventional fusion welding of titanium alloys must be performed in inert gas atmospheres with tightly controlled conditions due to the reactive nature of Ti alloys. On the other hand, the significant differences in physical and chemical properties of the two dissimilar materials will lead to chemical, mechanical and structural heterogeneities [6–11].

The direct bonding of titanium alloy to stainless steel exhibit the formation of various types of intermetallic compound formed in the diffusion zone due to the limited solid-solubility of Fe, Cr, Ni and Ti with each other and the bonding temperature plays a critical role in the formation of intermetallic phases, which makes the transition joints brittle. The formation of an intermetallic phase also causes the problem of formation of residual stresses resulting from thermal expansion mismatch [12–17]. In an earlier investigation, solid state diffusion bonding was carried out of Ti–6Al–4V alloy to 304 stainless steel and a maximum tensile strength of ~342 MPa and shear strength of ~237 MPa have been achieved at 800 °C for 5.4 ks and it was also observed that the bond strength drops due to the increase in the thickness of intermetallics and residual stress [18]. Residual stresses and brittle intermetallics near the interface of the transition joints can be minimised by using an appropriate intermediate material. Interlayer used in titanium alloy and stainless steel joints has several obvious advantages such as: low residual stress in the indirect bonded joint because the interlayer material serves as a buffer for the stress and low pressure required within the bonding zone during a joining process [19,20]. In this context, Ni alloy can be considered as a useful intermediate material for its satisfactory corrosion resistance. Literature reports that shear strength of 147 MPa was obtained for diffusion bonded Ti–6Al–4V and 304 SS joint when, processing was carried out at 850–880 °C for 10–20 min under 10–15 MPa pressure using a 30 μm thick Ni interlayer [21], however direct bonding of these two dissimilar materials results in lower bond shear strength of ~72 MPa [22]. Eroglu et al. [23] reported that diffusion bonding was carried out of Ti–6Al–4V alloy and micro-duplex stainless steel with copper interlayer and maximum shear strength of ~107 MPa was achieved at 900 °C for 5 min under 0.2 MPa pressure and at 100 K/min heating rate. Vigraman et al. [24] diffusion bonded Ti–6Al–4V and 304L stainless steel at the temperature range of 875 °C to 950 °C and Tan et al. [25] also mentioned that grain

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growth was very high in the temperature range of 700–800 °C for Ti–6Al–4V under strain, and it was slow in between 850 and 950 °C. Reports concerning the mechanical properties of the diffusion bonded joints formed between these two dissimilar materials are scanty. In the present study, diffusion bonding was carried out between titanium alloy and micro-duplex stainless steel using nickel alloy as an intermediate material and the processing temperature and times were varied to obtain a good combination of strength and ductility. The present study focuses attention on the characteristic features of the diffusion interfaces of the bonded joints and their effects on the strength of the diffusion bonded joints.

2. Experimental procedure

2.1. Materials

Micro-duplex stainless steel (MDSS) and titanium alloy (TiA) were used in the form of 35 mm diameter rod in hot rolled condition. 150 μm thick nickel alloy (NiA) interlayer was used as an intermediate material. The chemical compositions and room temperature mechanical properties of the base metals and intermediate materials are presented in Tables 1 and 2. 30 mm long and 15 mm diameter cylindrical samples were machined from 35 mm diameter parent metals.

2.2. Joints processing

In all cases, mating surfaces of micro-duplex stainless steel and Ti alloy samples were prepared by conventional grinding and polishing technique to obtain a surface roughness of ~0.11–0.17 μm. The nickel alloy foil of 150 μm thick was used as an intermediate material and both the side of the interlayer surfaces were polished in the same fashion. The mating surfaces were cleaned in acetone and dried in air. The MDSS |NiA |TiA assembly was kept in contact in a fixture and was inserted in a vacuum chamber. The diffusion bonding was carried out in the temperature range of 800–950 °C for 75 min and at 950 °C for 15 to 90 min in steps of 15 min in $(2–5)\times10^{-4}$ Pa vacuum. The compressive stress of 4 MPa was applied along the longitudinal direction of the sample. Heating was done at the rate of 0.24 °C s^{-1} at the time of processing and after the operation; the samples were allowed to cool in vacuum at a cooling rate of 0.1 °C s^{-1} up to 300 °C.

2.3. Micro-structural characterizations

For metallographic examination, the bonded joints were sectioned longitudinally to the bond line, grounded and polished. Polished surfaces of bonded couples were examined in a scanning electron microscope (JSM-5510, JEOL) in back scattered mode (SEM–BSE) to obtain finer structural details in the diffusion zone. The electron probe microanalyser (CAMECA Sx 100) was used to get the elemental concentration profiles across the diffusion interfaces. The k_α lines of Ti, Fe, Ni and Cr are generated at an operating voltage of 15 kV and specimen current of 12×10^{-8} A. The LiF crystal was used to diffract the corresponding characteristic x-ray radiation. Fracture surfaces of bonded samples were observed in secondary electron mode of SEM (JSM-5510, JEOL) using energy dispersive spectroscopy (Thermo Electron Corporation-Noran System Six C10018) to reveal the nature and location of failure under loading.

2.4. Mechanical properties evaluation

Tensile properties of the transition joints were evaluated in a universal testing machine (Instron 4204) at a crosshead speed of 8.33×10^{-3} mm s^{-1} at room temperature. Cylindrical tensile specimens were machined as per ASTM specification E8M-97 with gauge diameter and length of 4 mm and 20 mm, respectively. The interlayer was at the centre of the gauge length. Shear strength of bonded joint was evaluated at room temperature using a screw tensile testing machine set at a crosshead speed of 8.33×10^{-3} mm s^{-1}. Shear test specimens were machined to a diameter of 10 mm. Four samples were tested at each process parameter to check the reproducibility of results. Micro-hardness measurements on the polished surface of the bonded sample were carried out on a diamond micro-indenter using a 20 gf load for 15 s duration.

3. Results and discussion

3.1. Interfaces microstructure of the diffusion bonded samples

Bonding temperature and time are most important factors in diffusion bonding, as it strongly influences the characteristics of the diffusion bonded joints. The interfaces microstructure, diffusion layer thickness, and phase composition of the reaction zone depend on the bonding temperatures and times. The SEM–BSE images of MDSS–NiA–TiA bonded joints are given in Fig. 1. From the SEM–BSE images, diffusion interface are without any discontinuities and voids. Atoms from the substrates and the Ni alloy interlayer diffused continuously towards each other in both the MDSS–NiA (Fig. 2) and NiA–TiA (Fig. 3) interfaces during diffusion bonding.

3.1.1. At the MDSS–NiA interface

The SEM–BSE micrographs and EPMA elemental concentration profiles of the MDSS–NiA diffusion interface of the bonded samples are shown in Figs. 2 and 4(a), respectively. From the SEM–BSE images, interface region is clearly visible. The MDSS side is combination of bright (austenite phase) and shaded (delta ferrite phase) phases and in the interface region at stainless steel side, bright layer has been observed for all the processing

Table 2
Mechanical properties of the base metals at room temperature.

Alloy	Shear strength (MPa)	Ultimate tensile strength (MPa)	Fracture elongation (%)
Ti–6Al–4V	643.5	978.0	20
MDSS	501.6	660	33

Table 1
Chemical compositions of the base metals (wt%).

Alloy	C	Fe	Ti	Mn	Si	S	P	Cr	Ni	Al	V	O	N	Mo
Ti–6Al–4V	0.02	0.10	Bal	–	–	–	–	–	–	6.1	3.9	0.18	0.012	–
MDSS	0.04	Bal	–	0.77	0.4	0.005	0.014	26.5	5.0	–	–	–	0.02	–
Ni alloy	–	15.56	–	–	–	–	–	–	Bal	0.7				4.9