Microstructure and strength of diffusion-bonded joint between nickel aluminide $Ni_{75}Al_{25}$ and AISI 316 L stainless steel using a nickel interlayer

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Abstract

Diffusion bonding between nickel aluminide $Ni_{75}Al_{25}$ and 316 L austenitic stainless steel using a nickel interlayer was carried out at 1000 °C under vacuum for various hold times. The microstructures of the interface of joints were analysed by optical and scanning electron microscopy (SEM). Micrographs demonstrated that excellent bonding formed continuously along the interface. Chemical compositions of the interface of the bonded samples were determined using energy dispersive spectroscopy (EDS) and X-ray mapping studies were made on the fractured surface of all the specimens. Analysis results showed that reaction occurred between the base metals and the nickel interlayer. After welding process, shear tests applied to the bonded samples to determine shear strength of joints. Test results indicated that the maximum shear strength was 238 MPa for the bonded sample treated for 4 h.

K e y w o r d s: nickel aluminides, stainless steel, bonding, electron microscopy

1. Introduction

With ever increasing the demand of metallic materials with better performance in specific strength, creep strength and oxidation resistance, works have focussed on developing intermetallic aluminides, including iron aluminides, nickel aluminides and titanium aluminides [1]. Ordered intermetallic compounds are of interest for high temperature application because of their potential for high temperature stability, high creep resistance, high melting point, and low density. Among the intermetallics, compounds based on the aluminides are of particular interest because many of them possess oxidation resistance due to their ability to form protective oxide films on surfaces [2]. The aluminide Ni_3Al is of interest because of its excellent high temperature strength, low density, high fatigue resistance, and high temperature oxidation resistance at elevated temperatures [3]. Weldability is a specific issue related to fabrication technologies that is a major concern for Ni_3Al alloy. It is clear that the ability to weld nickel aluminides will greatly increase the opportunities to use them in engineering applications. Earlier studies of welding of Ni_3Al have mainly focussed on fusion weldability using gas tungsten arc (GTA) and electron beam welding (EB). These studies confirmed that Ni_3Al alloys were susceptible to both heat affected zone (HAZ) cracking and solidification cracking and they showed that cracking susceptibility depended on both alloy composition and welding parameters. Subsequent studies examined the behaviour of 0.01–0.25 wt.% B containing alloys in considerable detail. Results showed that the alloy containing 0.02 wt.% B was most resistant to the combined effects of HAZ and solidification cracking. Other works have examined the effect of Cr, Hf and Zr as alloying elements in B-doped Ni_3Al alloys [4–6].

Austenitic stainless steels are noted for high strength, exceptional toughness, ductility, and formability. They exhibit considerably better corrosion resistance than martensitic or ferritic steels and also have excellent strength and oxidation resistance at elevated temperatures [7]. The fusion weld of these steels is usually the part of a system with reduced corrosion

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resistance and low-temperature toughness, and therefore in many cases it is the limiting factor for material application. The heat of fusion welding also leads to grain coarsening in the heat-affected zone and solidification cracking in the weld metal of stainless steels [8].

Diffusion bonding is a solid state joining technique and has been applied successively for titanium alloys, aluminium alloys, steels, and intermetallics. This technique provides novel joining operation for similar and dissimilar materials without gross microscopic distortion and with close dimensional tolerance [9–11]. The majority of materials used in the engineering application involve multi-component system. A weld joint of dissimilar materials under external stress usually represents a critical point in many technical applications covering elevated temperatures. The investigation of the relationships among the element/phase redistributions, the microstructure at various points across the weldments, and local mechanical properties represents a method that is suitable for the evaluation of long-term mechanical/microstructure stability of weld joints. In the case of weld joint applications at elevated temperatures, the mechanical properties can be related to chemical composition and phase transformation processes in the diffusion-affected zone [12, 13].

A few studies have been reported on solid state welding of nickel aluminides. In a recent study, Ni_3Al alloy and AISI 304 stainless steel were bonded with the solid state welding [14]. More recently, the diffusion bonding of Ni_3Al has been reported by author and his co-worker. Good results were obtained from this study [15]. In the present paper, $Ni_{75}Al_{25}$ alloy and AISI 316 L stainless steel were bonded at 1000 ℃ under vacuum for various hold times. Pure nickel was used as an interlayer to prevent the formation of stable aluminium oxides at the bond region during diffusion joining. The microstructures of the interface of joints were examined and the shear strength of the bonded samples was considered by shear tests.

2. Experimental procedure

The alloy $Ni_{75}Al_{25}$ used was produced by arc melting under argon atmosphere from nickel and aluminium of 99.99 % and 99.7 % purity, respectively. AISI 316 L austenitic stainless steel was received from private company. The cylindrical samples of 6 mm length and 8 mm diameter were machined from the cast $Ni_{75}Al_{25}$ alloy and 316 L stainless steel. Surfaces of the samples were prepared by conventional metallographic techniques and cleaned with acetone. And then the surfaces of $Ni_{75}Al_{25}$ samples were immediately electroplated with electrolytic pure nickel. The coating thickness was measured as around 10 μm. The surfaces of coated samples and stainless steel samples were brought into contact. The samples were then placed in the chamber of the diffusion welding equipment. The diffusion bonding experiments were performed at 1000 ℃ for 1 h, 2 h and 4 h in vacuum of 2×10^{-3} Pa. Load of 5 MPa was applied along the longitudinal direction of the sample. The heating rate was

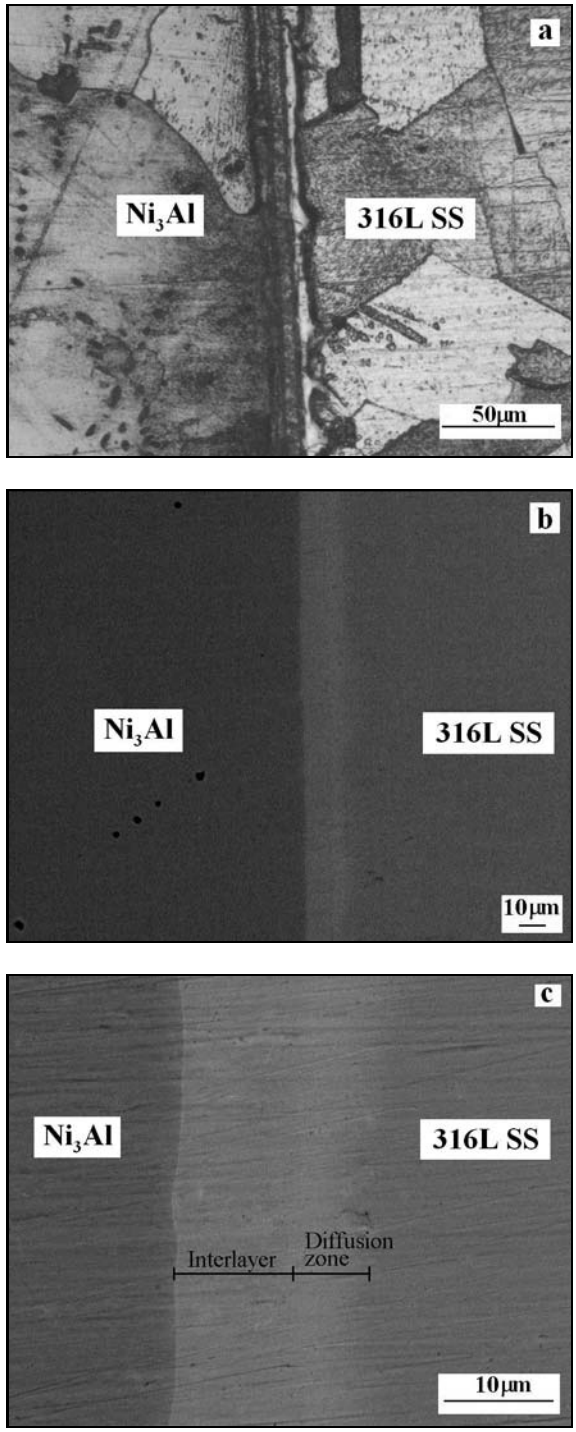

Fig. 1. Micrographs of the bonded sample for 4 h: (a) optical micrograph, (b) back-scattered electron image, (c) BSE image taken at higher magnification.

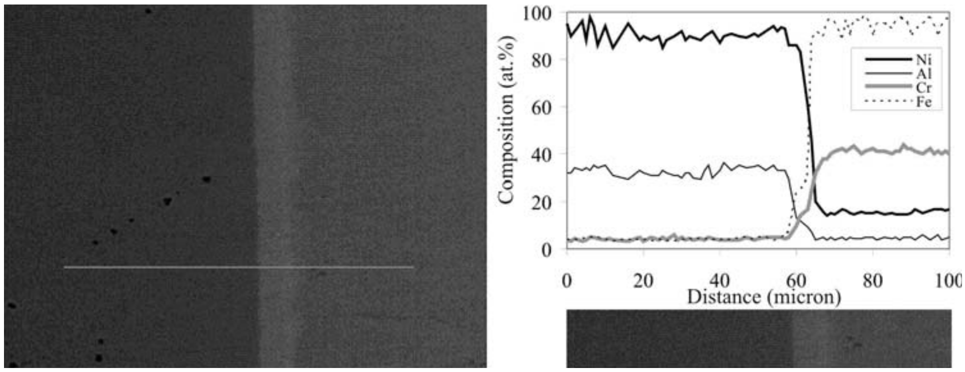

Fig. 2. Energy dispersive X-ray spectroscopy line scan analysis of the bonded sample for 4 h.

0.5 ℃ s^{-1}. After welding process, the bonded samples were cooled to the room temperature in the chamber.

Bonded samples were cut perpendicular to the bonding interface. The specimens were prepared according to standard metallographic procedures. Both sides of the specimens were etched by a mixture of H_2O (30 ml), HNO_3 (30 ml), HCl (20 ml), and HF (20 ml). The microstructure was observed in a light microscope. Polished samples were also examined in scanning electron microscope using back-scattered mode (SEM-BSE) to reveal the diffusion-bonded interface. The EDS line analysis and the EDS point analysis were done to observe the chemical composition of the bond interface of joints. Microhardness values were measured on both sides of the bonded samples by means of Vickers indenter with a load of 100 g. Special testing apparatus was designed to determine bond shear strength of the small bonded samples [10]. Bonded samples were inserted in the testing apparatus and the testing apparatus was placed on a tensile machine with a full load of 40 kN. Tests were carried out at room temperature with a loading speed of 0.5 mm min^{-1}. Fracture surfaces of joints were observed by scanning electron microscopy and X-ray mapping studies were made on the fractured specimen samples.

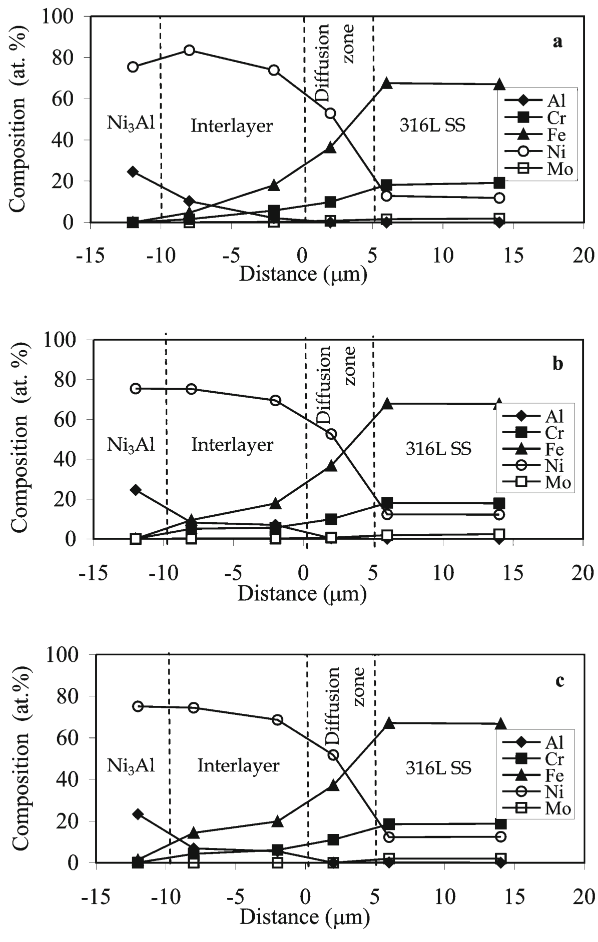

Fig. 3. Composition of Ni, Al, Fe, Cr, and Mo atoms from the bond centre to both sides of the bonded samples for (a) 1 h, (b) 2 h and (c) 4 h.

3. Results and discussion

The optical micrograph and SEM-BSE micrographs of the bonded sample for 4 h are shown in Fig. 1. All bonded samples exhibited good bonding without any micropores and microcracks along the interface. As seen from the micrographs, diffusion zone formed between nickel interlayer and stainless steel. The micrographs demonstrate that there is no change in the thickness of the interlayer with increase of bonding time. Energy dispersive X-ray spectroscopy line analysis and X-ray point analysis revealed the distribution of alloy elements from the diffusion zone into both sides of joints (Figs. 2 and 3). Analysis results indicated that interdiffusion between the nickel interlayer and the base metals was significant. During bonding, aluminium, chrome and iron atoms migrated from the nickel aluminide matrix and stainless steel matrix into the nickel interlayer. While the content of iron and chrome in the nickel interlayer increased

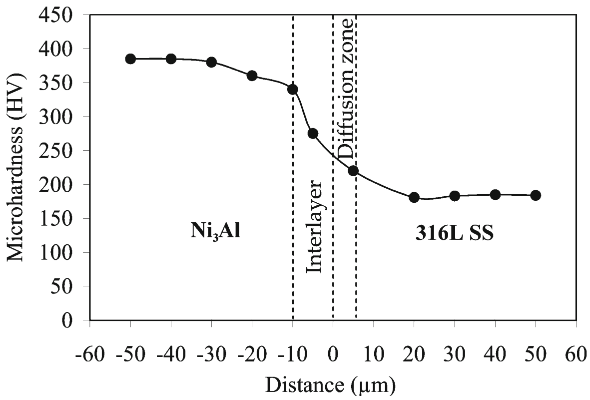

Fig. 4. Microhardness profiles of the bonded samples for 4 h from the bond centre to both sides.

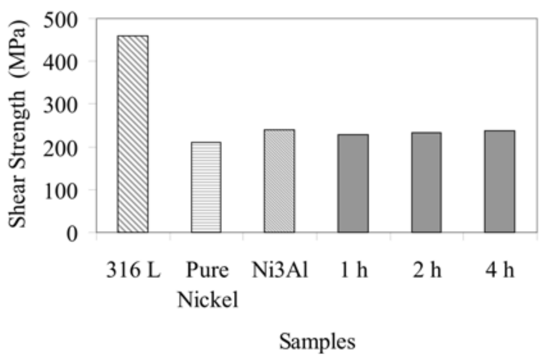

Fig. 5. Shear strength of the bonded samples for 1 h, 2 h and 4 h, nickel aluminide $Ni_{75}Al_{25}$, 316 L SS and pure nickel.

with increasing the process time from 1 h to 4 h, aluminium content decreased. EDS results show that the chemical composition of the diffusion zone for all the bonded samples is very similar.

Microhardness values of the bonded sample for 4 h from the bond centre to both sides are given in Fig. 4. According to the results of test, microhardness values at the bond region for all bonding times are similar. While the hardness of the diffusion zone is around 220 HV, the hardness of nickel interlayer at the bond region is around 275 HV. Normally, the hardness of pure nickel annealed at 1000 ℃ for 4 h is 125 HV. Hardness of the nickel interlayer at the bond region increased because the aluminium, chrome and iron atoms migrated into the interlayer at the bonded samples.

Shear strength of the joints was identified along the bond line. The shear strength of the joints, nickel aluminide, 316 L stainless steel and pure nickel is shown in Fig. 5. To compare the shear strength of joints with that of base metals and pure nickel, the base metals and pure nickel were annealed at 1000 ℃ for 4 h and cooled to the room temperature in chamber. Test results demonstrated that the shear strength values of the joints smoothly increased with increasing the bonding time. The highest shear strength of 238 MPa was obtained at the joint for 4 h. The value is higher than that for an annealed pure nickel and is very close to the base alloy $Ni_{75}Al_{25}$.

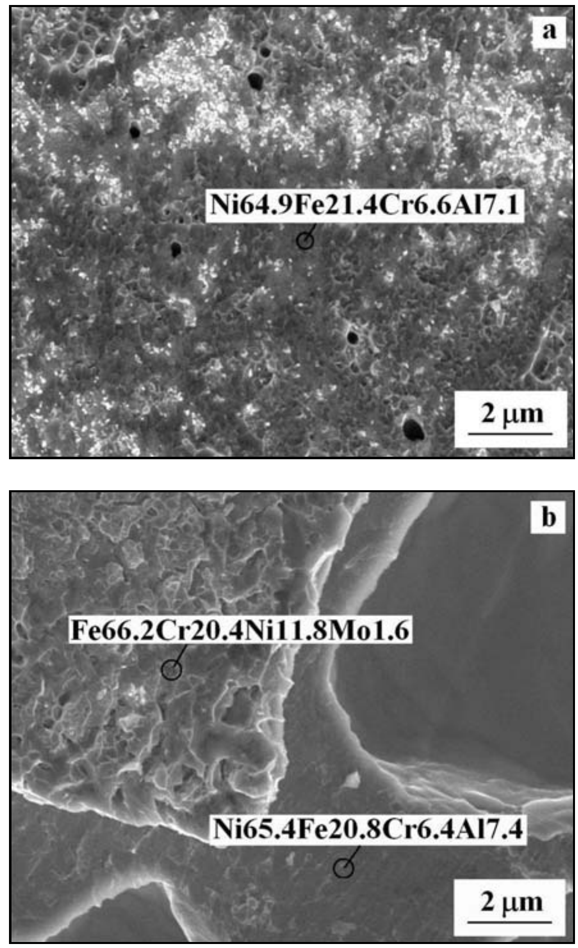

Fig. 6. Micrographs of fractured surfaces of the bonded sample for 4 h: (a) 316 L stainless steel side, (b) $Ni_{75}Al_{25}$ side.

Micrographs of the fractured surfaces of the bonded samples for 4 h are shown in Fig. 6. X-ray mapping analysis taken from the fractured surfaces revealed that Ni, Fe, Cr, and Al atoms existed on the fractured surfaces (Fig. 7). These findings are consistent with analysis results obtained from the bond region. In addition, these results confirmed that the fracture took place around the bond region during the shear test.

4. Conclusion

Diffusion bonding of $Ni_{75}Al_{25}$ alloy to 316 L stainless steel with a nickel interlayer has been achieved. The micrographs clearly indicate a sound bonding at

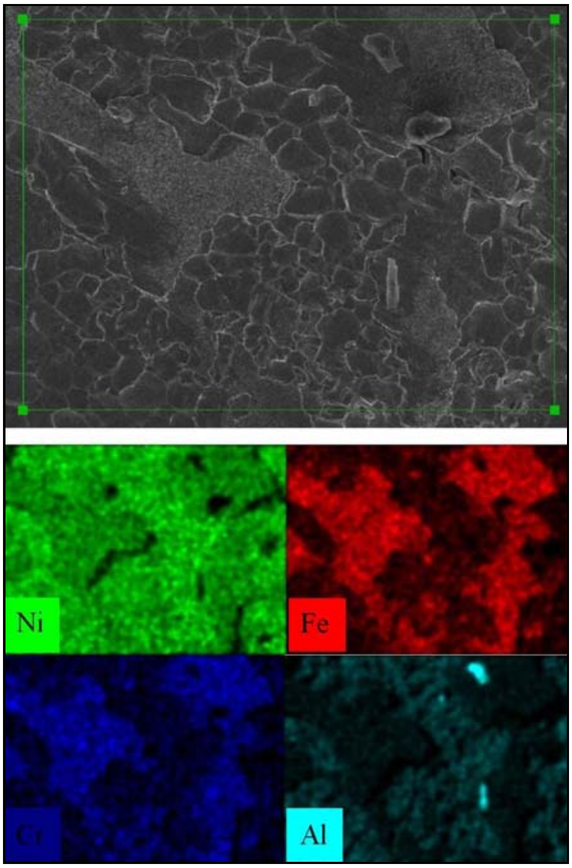

Fig. 7. X-ray mapping of fractured surfaces of $Ni_{75}Al_{25}$ side of the bonded sample for 4 h.

the bond region, which is free from micropores and microcracks. Pure nickel used as an interlayer prevented the formation of stable aluminium oxides at the bond region during diffusion joining. Energy dispersive X-spectroscopy and X-ray mapping results indicated that aluminium, iron and chrome atoms migrated from the base metals to the nickel interlayer. As a result of this situation, hardness of the nickel interlayer at the bond region increased. The shear strength of the joints smoothly increased with increasing the process time and the maximum shear strength was found as 238 MPa, which was very close to the shear strength of $Ni_{75}Al_{25}$ alloy.

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