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ORIGINAL ARTICLE

Characterization of a high strength Al-alloy interlayer for mechanical bonding of Ti to AZ31 and associated tri-layered clad

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Abstract The Al 6081 alloy is proposed as a favorable interlayer alloy with satisfactory deformability characteristics; high strength; least reactivity and melting temperature for high temperature joining of pure Ti and AZ 31. Titanium and Magnesium sheets with Al–0.81 Mg–0.9 Si alloy interlayer plate were joined by cold-roll bonding and subsequent annealing treatment. The maximum strength after annealing at 550 °C is due to the combined effect of the precipitation strengthening of Al–Mg–Zn interlayer and static strain aging. The most pronounced increase in the Vickers microhardness (from 49.2 to 74.5 Hv) was observed in the Al 6081 interface with AZ31 and Ti, thus indicating Al 6081 as a sound bonding interlayer with a lower melting temperature, initial excellent deformability and high strength after joining. With the increase in heat-treatment temperature, the tensile strength increased initially up to 550 °C and then decreased with the increase in annealing temperature to levels above 550 °C. The threshold deformation is about 44% of the total rolling reduction in a single rolling pass. The highest mechanical properties were 35 MPa in the composite – which was obtained by 550 °C/2 h annealing treatment.

1. Introduction

With the advancement of technology, the demand for leading-edge materials with enhanced properties and various functions increased [1–6]. It has become more difficult to satisfy the combination of various properties such as superior environmental-resistant characteristics, mechanical and biochemical properties in a single material. To meet such demands, clad materials in which different metals and alloys-with various properties were joined – have been developed and used in various industrial fields [1–3]. The properties of clad materials

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are determined by the selection of component materials to be joined and the stacking structure of different materials with various thicknesses and interface structure [3,5,6]. Several methods such as extrusion, rolling, electro-plating, overlay welding and explosive welding have been used for the clad material production and, among these methods, the rolling is one of the most cost-effective and productive processes [1–3,5]. Titanium has excellent corrosion resistance and stability in gaseous and aqueous environment and excellent specific strength compared to steels. Carbon steel has good strength and excellent cost advantage over titanium, but less environmental stability and corrosion resistance. Recently, the efforts to develop mechanically reliable Ti/steel clad [7] material have increased considerably driven by the need for materials with excellent corrosion resistance, good environmental stability, high specific strength and low production cost. A thin layer of expensive corrosion-resistant Ti alloy provides excellent corrosion protection while the thicker – but less expensive high-strength – carbon steel ensures adequate structural strength in Ti/steel clad. Titanium clad steel plates can be used in a variety of industrial fields including shipbuilding, construction and manufacturing of various chemical tanks. More specifically, roll-bonded Ti/steel clad plates are likely to be the economic solution for corrosion resistant applications in refineries, oil and gas production, chemical industry as well as in desalination plants and marine power plants. Cladding titanium/steel with mechanical reliability – at low temperatures – is difficult because of the high melting temperature and low mutual solubility [2,8–10]; explosive welding and diffusion bonding have been frequently used in the industry. An important challenge in titanium cladding is to obtain an interface with an acceptable bonding strength. During high temperature processing, titanium can react both with iron and with carbon, and forms brittle TiC and Fe–Ti compounds in contact with steel which decreases the interfacial strength [2,15].

Explosive welding with very short process time may yield a limited intermetallic compound, but is known to be an expensive process. In case of diffusion bonding, however, brittle intermetallics are likely to form at high temperatures, which may induce easy delamination and interface fracture. Therefore the optimum condition for diffusion bonding that ensures proper interface bonding – with non-excessive intermetallics at the interface – should be established [9,12–15]. In order to find a way to prevent the formation of brittle intermetallics between Ti and steel during high temperature diffusion bonding, the effects of metal interlayer such as Ni and Cu on the interfacial reaction were studied [9,12]. In this study, the cladding Ti and Al 6081 with magnesium AZ 31 interlayer was carried out at room temperature processing using a high plastic deformation processing. The mechanical properties were, in turn, characterized. The Ti–AZ31 layer was sandwiched by Al plates and the three layers of Ti–Al–AZ31 were clad using "Hot isotatic Press" (HIP). The effect of post-bonding heat treatment at low temperatures on the interfacial properties and the mechanical performance – in the tri-layered clad material – were also studied. In addition the design concept for an Al interlayer used in this study for cladding Ti and AZ31 was thoroughly described.

2. Experimental program

For this experimental program, Tri-layered Ti/Al–0.81 Mg–0.9 Si/AZ31 clad plates were produced by hot isotatic pressing. An Al–0.81 Mg–0.9 Si sheet with a thickness of 1.8 mm was inserted between Ti – with 2 mm thickness – and AZ31 sheets – with a thickness of 2 mm. They consequently exhibited hot isotatic pressing; processed under the pressure of 15 tonnes for 1, 2 and 3 h. Before HIP processing, the surfaces of Ti, Al 6081 and AZ31 sheets were degreased in acetone and the intimate surfaces between these sheets were scratched with #80 abrasive papers before stacking for HIP process. The clad plate after HIP bonding had a total thickness between 3.8 up to 4.2 mm according to temperature and time. Ti plates used in this study are of the commercial purity of 1100 ppm oxygen; Al 6081 plates had the composition of Al–0.81 Mg–0.9 Si; Magnesium alloys with composition of major elements 3.1% Al and 1.05 Zn of commercial as mentioned in Table 1. After HIP processing, composite clad plate was cooled under time control in furnace by a rate of 10 °C/min to examine the effect of cooling rate on the overall mechanical performance. To examine the variation in the hardness across the interface, Vickers microhardness measurements were conducted through a Vickers hardness tester (Zwick/Roell ZHV10). Vickers hardness was obtained at the mid-region of each component plate and at the interface of Ti/Al as well as Al/AZ31. Microstructures of interfaces were observed by an optical microscope and scanning electron microscopy. To evaluate the mechanical performance of clad materials, tension tests were performed using a Universal Materials Testing Machine (Zwick/Roell Z100). Tensile specimens of standard specimen were elongated at a strain rate of 1 mm/min at room temperature. A scanning electron microscope (SEM) (JEOL 5410) at 293.9 K and 35% humidity equipped with energy dispersive X-ray spectroscopy (EDX) and an X-ray diffractometer (XRD) were used to analyze interface morphology and detect the compositions, and to identify intermetallic formed during the annealing treatment. The purpose is to evaluate the effect of temperature and time on the mechanical properties of Ti, annealed aluminum (6081) and AZ31.

3. Results and discussion

Design architectures as well as ply numbers are being considered for composite processing. The chemical compositions of the alloys sheets are shown in Table 1. As-received samples were

Table 1 Chemical composition of investigated alloys (Wt.%).

Alloy	Al	Cr	Fe	Cu	Zn	Si	Mn	Mg	Pb	Ca	Ni	Ti
Al 6081	Bal.	–	–	0.05	–	0.01	0.05	0.088	0.002	–	0.1	–
Ti (pure)	–	–	0.25	–	–	< 0.01	–	–	0.004	–	–	Bal.
AZ 31	3.1	–	–	< 0.05	1.05	< 0.15	0.2	Bal.	1	< 0.04	< 0.005	–