Materials Characterization 134 (2017) 163–171

Contents lists available at ScienceDirect

Materials Characterization

journal homepage: www.elsevier.com/locate/matchar

Interface-correlated bonding properties for a roll-bonded Ti/Al 2-ply sheet

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ARTICLE INFO

Keywords:
Ti/Al 2-ply sheet
Roll bonding
Annealing
Interface
Bonding strength

ABSTRACT

We investigated the influence of annealing conditions on the interface-correlated microstructural evolution and subsequent bonding properties of a warm roll-bonded Ti/Al clad sheet. A $TiAl_3$ intermetallic compound layer with a thickness of 160 nm was initially generated at the joint interface between the Ti and Al alloys by warm rolling. When the annealing time and temperature were increased to a maximum of 6 h and 650 °C, respectively, the thickness of the $TiAl_3$ layer increased to 320 nm. The feasible annealing conditions for the optimum bonding strength were within 550 °C-6 h and 600 °C-3 h. An improvement in the bonding strength between Ti and Al is strongly correlated with the generation of considerable metallurgical bonding. This is manifested in the zipper-like failure mode that occurs at the $TiAl_3$ joint interface for a layer thickness of less than 300 nm.

1. Introduction

Multi-layered metallic sheets possess a dual advantage, as they retain the unique properties of its constitutive metals and offer economic benefits by the substitution of cost-effective metals [1–4]. Ti and its alloys possess advantageous properties such as excellent specific strengths, resistance to corrosion and oxidation, and biocompatibility [5–8]. However, poor formability and expensiveness hinder them from being widely utilized in various industries. For this reason, comprehensive efforts are underway to widen the applications of Ti and its alloys by substituting them partially with relatively inexpensive, lightweight, and deformable aluminum alloys.

To fabricate Ti/Al clad materials, several processes such as explosive bonding [9,10], roll bonding [11–14], diffusion bonding [15], or continuous casting [16–18] have been employed. Among them, the roll-bonding technology is widely preferred as it allows for cost-effective and continuous production. Although warm roll bonding between Ti and Al alloys can provide mechanical interlocking, a strong and extensive metallurgical bonding achieved at the interface is insufficient. Therefore, Ti/Al laminated sheets should be subjected to a post roll-bonding annealing treatment in order to control the interface diffusion and acquire the desired mechanical properties. The influence of annealing on the interface microstructure has been extensively studied. Many studies have reported that $TiAl_3$ was the first and the only phase generated between the parent Ti and Al alloys by annealing at around 600 °C, followed by a lateral growth of the layer in the direction parallel to the interface [19–22]. More recently, Assari and Eghbali [23] reported that the evolution of intermetallic compounds during solid-state diffusion between pure Ti and pure Al occurs in the sequence of $TiAl_3 \rightarrow TiAl \rightarrow TiAl_2$ with increasing consumption of the Al layer. $TiAl_3$ is the hardest intermetallic compound (IMC) phase among Ti_xAl_y IMCs, according to Van Loo and Rieck [24]. Yu et al. [25] recently reported that long-time annealing for 24 h at 600 °C reduced residual voids at interface and generated the highest yield strength and good ductility of thin Al/Ti/Al laminate. However, the effect of annealing conditions on the trade-off between an improvement in the overall bonding strength by proper metallurgical diffusion and the catastrophic debonding from the growth of IMCs at the interface between Ti and Al alloys has not been thoroughly investigated yet.

The aim of this study is to investigate the effects of annealing conditions on the microstructural evolution and subsequent bonding strength of roll-bonded 2-ply Ti/Al sheets. This study also proposes an interfacial bonding mechanism that focuses on the effect of the diffusion zone thickness on the bonding strength at the joint interface between Ti and Al.

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http://dx.doi.org/10.1016/j.matchar.2017.10.009
Received 21 July 2017; Received in revised form 24 September 2017; Accepted 7 October 2017

Table 1
Different post-roll-bonding annealing conditions adopted in this study.

Conditions	400 °C	450 °C	500 °C	550 °C	600 °C	650 °C
30 min	A1	B1	C1	D1	E1	F1
1 h	A2	B2	C2	D2	E2	F2
3 h	A3	B3	C3	D3	E3	F3
6 h	A4	B4	C4	D4	E4	F4

2. Experimental Procedures

The constituent metallic alloys used for the roll-bonding were: Commercially pure titanium grade 1 (99.6% purity; 0.15 mm thickness; 300 mm width), and aluminum 1050 (99.7% purity; 1.08 mm thickness; 300 mm width) sheets. After proper surface treatment by brushing and degreasing, a single-step warm roll-bonding was carried out at around 350 °C under a nominal thickness reduction of 38%.

The samples were then cut into 300-mm long and 10-mm wide longitudinal sections perpendicular to the rolling direction. These cross-sectioned strips were then annealed in a resistance furnace under an argon atmosphere for up to 6 h at temperatures between 400 °C and 650 °C. The post-roll-bonding heat treatments adopted in this study are summarized in Table 1. The schematics of the roll-bonding and heat treatment processes are illustrated in Fig. 1.

The Ti/Al clad sheets were cross-sectioned and mechanically polished for observing the interface microstructure. Field-emission scanning electron microscopy (FE-SEM, model: TESKAN MIRA II) was used to identify the microstructural evolution at the interfaces between the parent alloys. Electron back-scatter diffraction (EBSD) analysis was also carried out by the FE-SEM. To characterize the subtle microstructural changes at the sub-micrometer scale in the interface a few specimens for transmission electron microscopy (TEM) analysis were prepared by the focused ion beam technique (FIB, model: Quanta 3D FEG, FEI, USA). These specimens were then analyzed by TEM (model: JEM-2100F, JEOL, Japan) at an acceleration voltage of 200 kV.

Longitudinal, 10-mm wide, plate-type specimens were also prepared for the T-peel test (standard ASTM D1876, see Fig. 2(a)) that was performed at a deformation rate of 6 mm/min, to obtain the variation in the bonding strength. Fig. 2(b) shows the experimental setup of the T-peel test with the Ti/Al 2-ply strips. Fractographs of the peeled surface were observed by FE-SEM.

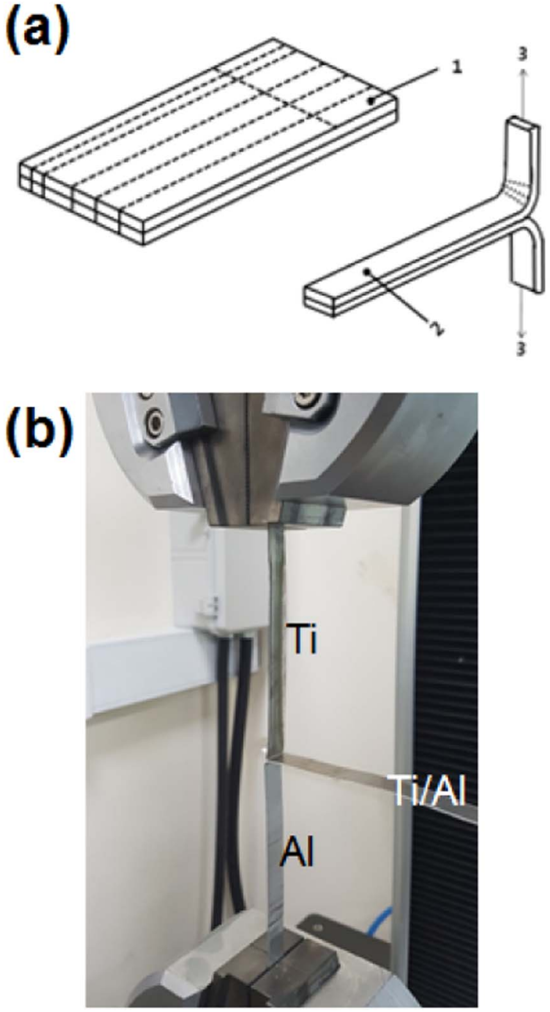

Fig. 2. (a) Schematic diagram of T-peel test and (b) experimental setup.

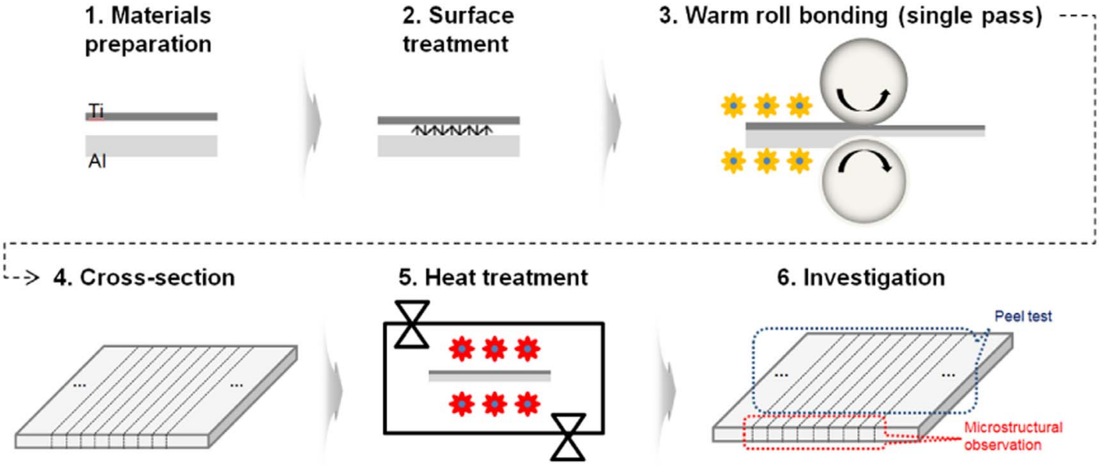

Fig. 1. Schematics of warm roll bonding and heat treatment processes for fabricating Ti/Al 2-ply laminated strips.