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Microstructure and mechanical properties of Al/Ti/Al laminated composites prepared by roll bonding

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ABSTRACT

Al 6061/Ti–6Al–4V/Al 6061 laminated composites were fabricated by hot-roll bonding. The effect of rolling temperature and reduction on the microstructure and mechanical properties of Al/Ti/Al laminated composites was investigated. The results show that the Al/Ti/Al laminated composites exhibited a good Al/Ti interfacial bonding. The reduction ratio of Ti to Al layer decreased with increasing rolling temperature and reduction. The development of microstructure through the thickness of Al layer was inhomogeneous. The number of high-angle boundaries and the misorientation angle across low-angle boundaries increased as the thickness position moved towards the surface of Al layer from the interface of Al/Ti. The initial grains near the surface of Al layer were markedly elongated at a certain angle to the RD and then fragmented into the equiaxed fine grains at larger rolling reductions. This inhomogeneity of microstructure can be attributed to the effect of the friction between the roll and sheet surface and the uncoordinated deformation between Al and Ti layers. The deformation inhomogeneity increased with increasing rolling reduction. For the laminated composites fabricated with rolling reductions of 27% and 38%, the yield and tensile strength increased to a maximum value at about 400 °C and then decreased with increasing rolling temperature. The laminated composites fabricated with a 45% reduction possessed lower strength in the temperature range from 400 °C to 450 °C than those with a 38% reduction due to the fracture of Ti layer.

1. Introduction

With the development of modern technology, single material hardly satisfies the increasing demands of properties. Laminated metal composites (LMCs), consisting of two or more metals, have been developed due to their improved fracture toughness, bending behavior, impact behavior, corrosion, wear and damping capacity [1,2]. A number of techniques have been developed to manufacture LMCs, such as explosive welding, roll bonding, diffusion bonding, extrusion and friction-stir welding. However, roll bonding has been extensively investigated because of its efficiency and economy. Roll bonding is a solid-state welding process in which multiple layers of similar or dissimilar metals are stacked together and rolled to a certain degree to produce a solid-state welding [3]. It has been reported that the roll bonding of metals is affected by various factors, such as rolling reduction [3–6], rolling temperature [4–6], rolling speed [5,7–9], initial thickness [5,7], rolling direction [7], surface roughness [5], and annealing treatment before and after the roll bonding process [6,7]. At present, roll bonding has been successfully applied to produce LMCs, including Cu/Nb [10], steel/steel [11], Ti/Al [12,13], Al/Al [4], Ag/Cu [14], Ag/Fe [15,16], Al/Cu [17–19], Al/Zn [6], Cu/Cu [2,5] and Al/Mg [20,21].

Ti/Al laminated composites have great potential for industrial applications due to their excellent mechanical properties combined with low density. In addition, the Ti/Al system is economically more attractive than monolithic titanium by the joining of relatively inexpensive aluminum. Recently, there are a lot of researches on the fabrication of Ti/Al laminated composite by roll bonding [12,13,22–25]. Ng et al. [22] investigated the asymmetric accumulative roll bonding (AARB) of aluminum–titanium composite sheets. It was found that both the tensile strength and ductility of the sheets increased systematically with roll diameter ratio. AARB not only led to a more refined grain size of the Al matrix but also promoted the development of a nanostructured surface layer on Ti. Pang et al. [23] studied the mechanical properties of Ti–(SiC_p/Al) laminated composite with nano-sized $TiAl_3$ interfacial layer synthesized by roll bonding. They found that the deformation compatibility of Ti and SiC_p/Al layers decreased with increasing rolling reduction due to the work-hardening of Ti layer. Luo and Acoff [12] used cold roll bonding and annealing to process

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Ti/Al multi-layered composites from elemental foils. It was observed that the entire Al-rich layer transformed into $TiAl_3$ after a few hours at a temperature of 650 °C. Chaudhari and Acoff [24] made titanium aluminide sheets using roll bonding and reaction annealing. Yang et al. [25] successfully synthesized Ti/Al multi-layered composites using accumulative roll bonding (ARB). They found that large shear strain, high strain rate, reversing rolling direction after each ARB cycle and the low thermal conductivity of Ti were critical factors for the formation of ultrafine equiaxed grains in Ti/Al multilayered composites. In the present work, Al 6061/Ti–6Al–4V/Al 6061 laminated composites were fabricated by hot-roll bonding. The effect of rolling temperature and reduction on the microstructure and mechanical properties of the Al/Ti/Al laminated composites was investigated.

Table 1
Chemical composition of AA 6061 aluminum alloy (wt%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.6	0.7	0.28	0.15	1.0	0.19	0.25	0.15	Bal.

Table 2
Chemical composition of Ti–6Al–4 V (wt%).

Al	V	Fe	C	N	O	Ti
5.8	3.7	0.03	< 0.01	0.01	0.09	Bal.

2. Experimental

The materials used in this study were AA 6061 aluminum alloy sheets with a thickness of 0.4 mm and Ti–6Al–4V foils with a thickness of 0.1 mm. The chemical compositions of the two materials are listed in Tables 1 and 2. The as-received materials were cut parallel to the transverse direction to produce 100 mm × 80 mm pieces. AA 6061 aluminum alloy sheets were annealed at 530 °C for 2 h followed by air cooling. The annealed aluminum sheets possessed an equiaxed grain structure and strong cube and R recrystallization textures, as shown in Fig. 1.

The annealed 6061 aluminum alloy sheets and Ti–6Al–4V foils were roughened with 80 grit SiC paper and then ultrasonically cleaned in absolute ethyl alcohol. The morphologies of the roughened surfaces are shown in Fig. 2. After the surface treatments, the aluminum sheets and titanium foils were stacked in the sequence of Al/Ti/Al as a sandwich with the roughened surfaces contacting each other and riveted together at one end. The riveted sheets were preheated at 300 °C, 350 °C, 400 °C, 450 °C, 500 °C and 550 °C for 8 min in an air furnace, and then immediately rolled to different reductions on a laboratory rolling mill with rolls of 230 mm in diameter. Single-pass reductions of about 27%, 38% and 45% were attempted at a rolling speed of 0.6 m/s.

The microstructures of Al layer in Al/Ti/Al laminated composites were revealed by anodic oxidation and observed using polarized light in an optical microscope. All micrographs were taken from longitudinal cross-sections as defined by the rolling direction (RD) and the normal direction (ND). Specimens for scanning electron microscopy were electropolished in a solution containing 950 ml methanol, 3 ml HNO_3 and 10 ml $HClO_4$ at a

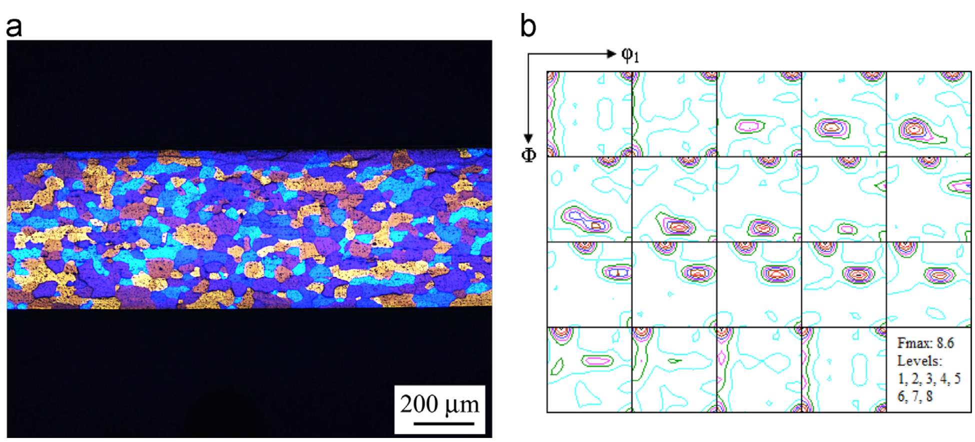

Fig. 1. (a) Microstructure and (b) texture of AA 6061 aluminum alloy after annealing at 530 °C for 2 h.

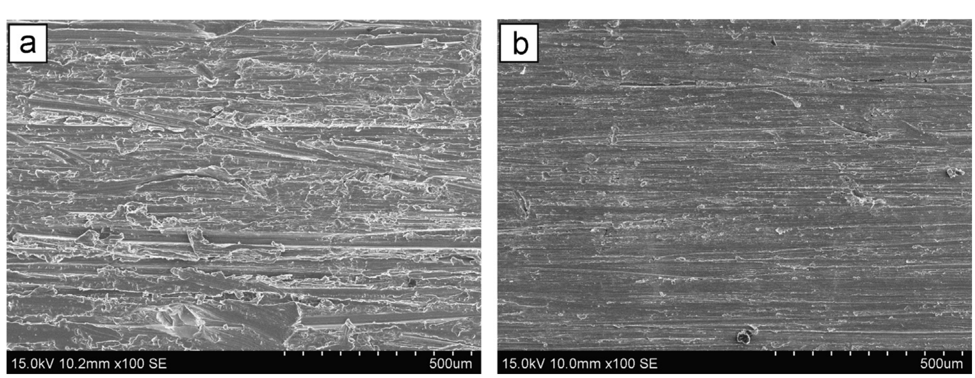

Fig. 2. Surface morphologies of (a) AA 6061 aluminum alloy sheets and (b) Ti–6Al–4V foils after grinding.