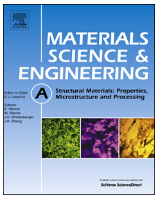
Materials Science & Engineering A 606 (2014) 205–213

Contents lists available at ScienceDirect

Materials Science & Engineering A

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



Influence of secondary warm rolling on the interface microstructure and mechanical properties of a roll-bonded three-ply Al/Mg/Al sheet

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ARTICLE INFO

Article history:
Received 24 December 2013
Received in revised form
1 March 2014
Accepted 24 March 2014
Available online 31 March 2014

Keywords:
Rolling
Mechanical properties testing
Al/Mg/Al sheet
Multilayers
Interface structure

ABSTRACT

We investigated the influence of annealing and secondary warm rolling on the microstructural evolution and mechanical properties of a roll-bonded three-ply Al/Mg/Al sheet. After annealing at 300 °C, the formation of an intermetallic compound (IMC) layer consisting of $Mg_{17}Al_{12}$ and Mg_2Al_3 was identified at the interface. Although the thickness of the IMC layer increased with increasing annealing or preheating time, secondary warm rolling after preheating at 300 °C for 10 min significantly reduced the thickness of the IMC layer below 1.5 μm. Also an equiaxed and homogeneous grain morphology of the constituent magnesium alloy was successfully introduced. This resulted in strongly enhanced elongation up to magnesium fracture by 14.5%.

1. Introduction

Hybrid materials and structures have received increasing attention because of their multifunctionality, which cannot be offered by any one material alone [1,2]. In order to achieve multifunctionality, there are a number of factors that need to be taken into consideration for the construction of hybrid materials, such as the choice of constituents, volume fraction, configuration, and the interface generated during hybridization [3]. Although new techniques such as adding spaces between layers expand the ability to design hybrid materials [3], one of the simplest approaches for designing hybrid materials is stacking plates layer by layer without spaces, so called “multilayered materials”.

Clad metal is as a type of hybrid multilayered material that consists of two or more dissimilar metallic alloys. These structures enable combinations of selective properties such as mechanical, thermal, and electromagnetic characteristics from the constituent metallic alloys to be simultaneously realized, properties that cannot be obtained from a monolithic alloy. The use of hybrid multilayered materials also enables the fabrication of structures that are lightweight and corrosion-resistant. In order to fabricate clad metals, many kinds of processes have been utilized, such as explosive bonding [4–8], roll bonding [9–12], diffusion bonding [13,14], continuous casting [15,16], and resistance seam cladding [17]. Among them, the roll-bonding process is the most widely used because it enables cost-effective continuous fabrication. It is well known that the mechanism of interface bonding during warm roll bonding is divided by three stages: (i) initiation of physical contact, (ii) surface activation during contact, and (iii) interactions between the dissimilar parent metals [18,19]. This means that mechanical contact or interlocking followed by considerable metallurgical bonding is a prerequisite to obtain sound joints at the interface.

Although there are many metallic alloys for that can act as cladding matrices, such as stainless steel [20,21], carbon steel [22,23], copper [2,24] and titanium [11,25–27], lightweight aluminum and magnesium alloys have been actively considered [28–33], which are desperately required in the automotive industry and for household appliances for worldwide environmental protection. Magnesium alloys in particular are known as a strong candidate material due to their extraordinary lightweight and high-specific-strength properties. However, magnesium and its alloys have two intrinsic drawbacks; poor formability at room temperature and poor corrosion resistance. In order to overcome these drawbacks, the possibility of cladding both sides of magnesium alloys with aluminum alloys in order to fabricate Al/Mg/Al three-ply laminates was recently investigated [34–37]. These laminates can offer beneficial properties such as enhanced corrosion resistance and improved mechanical performance. Although warm roll bonding between aluminum and magnesium alloys can yield mechanical interlocking followed by a degree of metallurgical bonding, it is insufficient to realize a strong, compact metallurgical bonding at the interface, together with improved deformation potential. Therefore, it is important for roll-bonded

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http://dx.doi.org/10.1016/j.msea.2014.03.082
0921-5093/© 2014 Published by Elsevier B.V.

Al/Mg/Al laminates to undergo heat treatment in order to improve the quality of the bonding properties. For instance, previous investigation by Macwan et al. revealed that proper annealing conditions had a significant influence on the marginal enhancement of tensile properties such as ultimate tensile strength and elongation to failure for Al/Mg/Al clad sheets, which was presumably correlated to the generation and growth of intermetallic compound (IMC) layers at the interface [37]. However, the influence of secondary warm rolling on the microstructural evolution at the interface and the subsequent mechanical properties of roll-bonded three-ply Al/Mg/Al laminates have not been reported yet according to the authors' knowledge. The aim of this study is to identify the influence of secondary warm rolling and annealing on the microstructural evolution and relevant mechanical properties of a roll-bonded three-ply Al/Mg/Al laminate.

Table 1
Chemical compositions of constituent Al and Mg alloys.

Al (1050)	Fe 0.26	Si 0.09	Ti 0.01	Mg 0.01	Al Bal.
Mg (AZ31B)	Al 2.99	Zn 0.76	Mn 0.30	Si 0.03	Mg Bal.

2. Experimental procedure

Commercially available 1050 Al alloy and AZ31B Mg alloy sheets were selected as roll-bonding partners; their chemical compositions are listed in Table 1. The initial dimensions of the 1050 Al and AZ31B Mg sheets were $400 \times 700 \times 1\ \text{mm}^3$ and $400 \times 700 \times 3\ \text{mm}^3$, respectively. After proper surface treatment (i.e., brushing and degreasing), three sheets in the stacking sequence of 1050 Al–AZ31B Mg – 1050 Al were subjected to preheating at 380 °C for several minutes followed by single-step warm roll bonding with an average reduction ratio of 35%.

From the roll-bonded Al/Mg/Al plates, several pieces from the center of the plates were cut into $100 \times 250\ \text{mm}^2$ samples in order to perform laboratory-scale annealing or secondary warm rolling as a type of skin pass. A resistance furnace was used for the heat treatment with no protective atmosphere at 300 °C for annealing times of 10, 30 and 60 min. Also, a series of single-pass, secondary warm rolling was carried out after preheating for 10, 30, and 60 min at 300 °C under a constant reduction ratio of ∼30%. A schematic description of the overall single-step roll bonding, heat treatment and secondary warm rolling was shown in Fig. 1. The post-roll-bonding treatments adopted in this study are summarized in Table 2. After secondary warm rolling, the average thicknesses of the constituent alloys were determined by measuring the samples at five different locations. The variation of both thickness and the fraction of the constituent alloys were plotted as

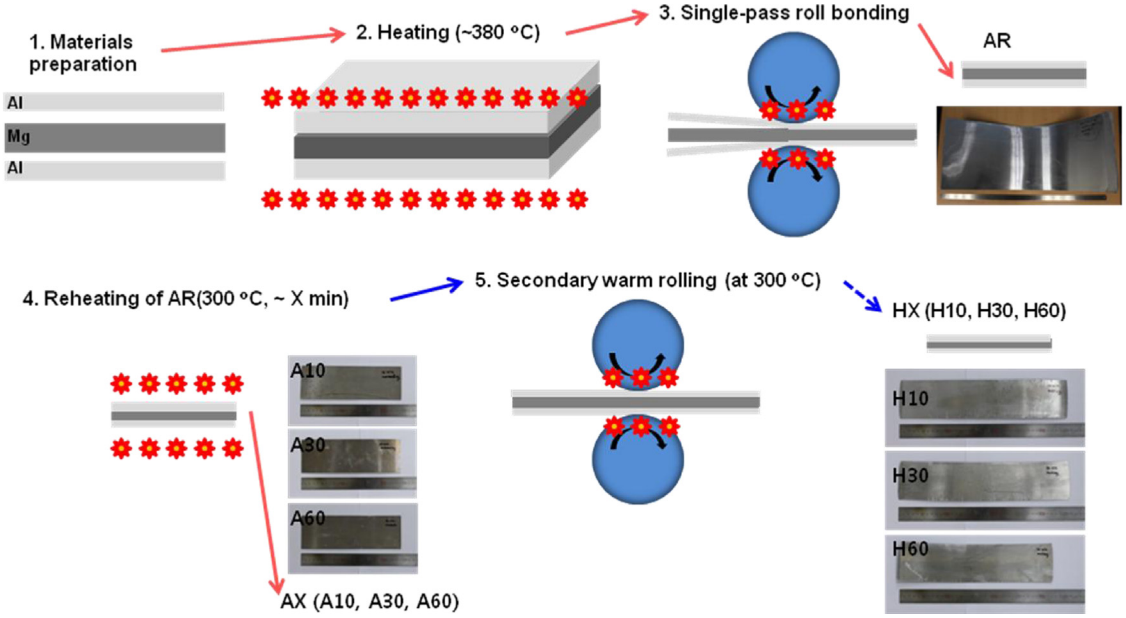

Fig. 1. Schematic of single-step roll bonding, heat treatment and secondary warm rolling for three-ply Al/Mg/Al clad sheets.

Table 2
Various post-roll-bonding treatments adopted in this study.

	Annealing time [min]	Sample number	Dimension [mm]
Single-step roll bonding	–	AR	$\sim 400 \times \sim 1000 \times \sim 2.6t$
Only annealing	10	A10	$\sim 100 \times \sim 250 \times \sim 2.6t$
	30	A30	$\sim 100 \times \sim 250 \times \sim 2.6t$
	60	A60	$\sim 100 \times \sim 250 \times \sim 2.6t$
Pre-heating + secondary warm rolling (Reduction ratio = 30%)	10	H10	$\sim 100 \times > 250 \times \sim 1.5t$
	30	H30	$\sim 100 \times > 250 \times \sim 1.5t$
	60	H60	$\sim 100 \times > 250 \times \sim 1.5t$