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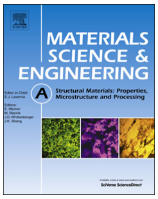

Influence of reduction ratio on the interface microstructure and mechanical properties of roll-bonded Al/Cu sheets

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ABSTRACT

Two-ply Al/Cu sheets were prepared via roll bonding with different reduction ratios. Al/Cu sheets fabricated below 50% of reduction ratio exhibited relatively equiaxed grains without interface reaction, which resulted in weak joint-bonding strength. However, both strong metallurgical bonding at interface and fine, elongated grains from constituent alloys adjacent to the interface were successfully introduced under the reduction ratio of 65%, leading to a strongly enhanced bonding strength of 17.1 N/mm together with an increased elongation up to fracture by 28%.

1. Introduction

Recently there is a growing interest for ‘hybrid’ metallic materials that will have the structural and functional characteristics of multiple constituent, which individual constituents of metallic alloys do not have [1,2]. There are a number of methods for fabricating metallic laminates but roll-bonding technology is the most common one due to its cost-effective continuous production ability for manufacturing multilayered clad metals [3–6]. Previous studies revealed that the formation of solid-state metallic laminates bonding involve three-stage steps: (i) initiation of physical contact, (ii) surface activation in contact, and (iii) interactions between the dissimilar parent metals [7,8]. Hence, mechanical joining or interlocking followed by feasible metallurgical bonding at the interface is indispensible to obtain sound joints between dissimilar metals.

Al–Cu bimetal plates offer a couple of beneficial properties such as reduced weight, formability, and corrosion resistance without much electrical conductivity expense as compared to monolithic pure copper or copper alloys [2]. Moreover, this combination of materials is economically more attractive than monolithic Cu, if the fabrication process for this bimetal becomes economically competitive. Some of the important process parameters for roll bonding of Al/Cu laminates are rolling temperature, reduction ratio during roll bonding, annealing temperature, and time after roll bonding. It was found that there is a critical post-annealing condition in order to achieve optimum bonding strengths between dissimilar metals [9,10]. However, it is difficult to bond dissimilar metals such as Al and Cu using warm roll bonding followed by a typical annealing step, because the complex Al–Cu intermetallic compounds (IMCs) include more brittle and harmful phases (i.e., AlCu and Al_3Cu_4) that are easily generated at elevated temperatures, which can be detrimental to the final mechanical performance of the composites [11–13]. Furthermore, it has also been documented that the existence of oxide layer at interfaces between parent Al and Cu alloys hampers them from metallurgical diffusion bonding, which degrades the interfacial bonding strength [14]. Therefore, it is necessary for Al/Cu combinations to control the initial stages of roll bonding process to avoid post-annealing steps and to study the effect of rolling strain on the interface and overall mechanical properties of an Al/Cu two-ply laminate. In the present study, we investigated the influence of reduction ratios during roll bonding between Al and Cu alloys on the microstructural evolution and subsequent mechanical properties of Al/Cu laminated composites.

2. Experimental procedure

Commercial aluminum alloy AA1050 and pure copper (UNS C 11000) sheets were selected as components of the laminated alloys. After proper surface treatments (i.e., brushing and degreasing), sheet materials (375 mm wide and ca. 500 mm long) were subjected to roll bonding with different reduction ratios ranging

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between 65% and 30%. The features of the roll-bonding technique can be found elsewhere [14]. Initial aluminum alloy thickness was controlled to obtain ~3 mm-thick Al/Cu two-ply laminated sheets having the same final thickness and Al/Cu ratio of ca. 7.25:1. The sample number and final thickness as a function of different reduction ratios are summarized in Table 1.

Since it is difficult to observe subtle microstructural changes in the interface at the sub-micrometer order, the interfaces of the Al/Cu joint were examined by transmission electron microscope (TEM, model JEOL JEM-2100F) at 200 kV. A focused ion beam (FIB, model Helios, Pegasus) instrument was used to mill surfaces in the interlayer of Al and Cu for subsequent electron back-scatter diffraction (EBSD) analysis. EBSD (step size: 35 nm) was conducted using a field emission scanning electron microscope (FE-SEM, model JEOL JSM-7401F, Jeol). The data were then interpreted using software for orientation imaging microscopy analysis, which was provided by TexSEM Laboratories, Inc. This analysis was performed for each section, and it included the reconstruction of maps for improving image quality, inverse pole figure coding, and kernel average misorientation. Uniaxial tensile tests were conducted using a screw-driven-type Instron 4206 testing machine at an initial strain rate of $10^{-3}\ s^{-1}$ at room temperature. Flat dog-bone tensile specimens (ASTM standard E8 sub-size) with gage length of 25 mm were prepared along the direction perpendicular to the rolling direction (RD) of the sheet materials. Tensile test specimens for constituent monolithic alloys were also prepared by cross-sectioning through the interfaces from two-ply tensile specimens using an electrical discharge machine (EDM) followed by parallel grinding. After cutting two-ply clad plate with a width of 10 mm and a length above 180 mm, bonding strength of the Al/Cu laminated sheet was measured by a roller drum-type peel test (standard ASTM D3167).

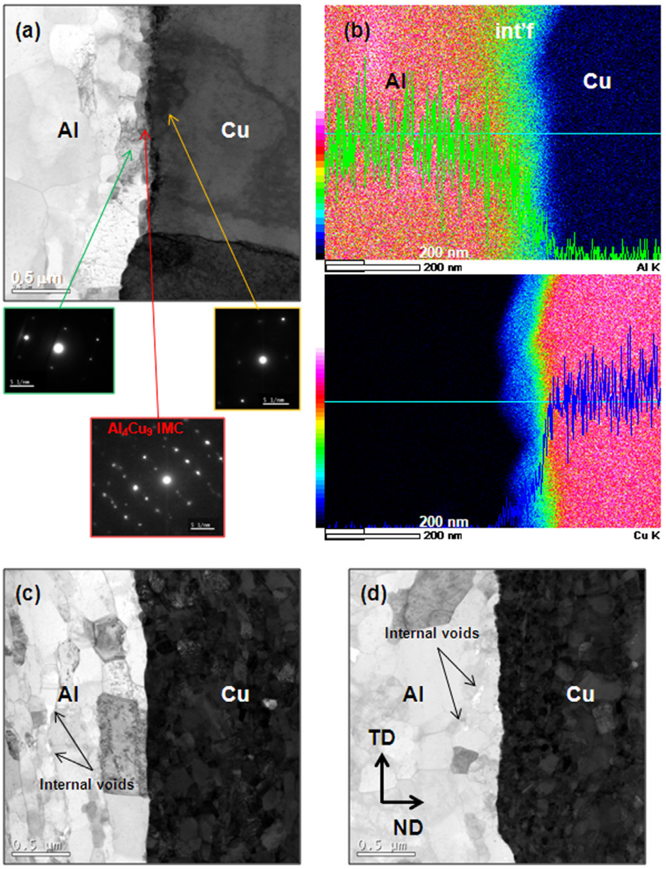

Fig. 1. Bright-field TEM images obtained close to the bonding interface of (a) Al/Cu two-ply sample #1 together with (b) elemental mapping, (c) sample #3, and (d) sample #5.

3. Results and discussion

Fig. 1(a, c, and d) reveals the bright-field TEM images at the bonding interface between Al and Cu from as-rolled samples #1, #3, and #5, respectively. From Fig. 1(a) a discontinuously generated reaction phase is noticeable, which has a thickness of 50–100 nm. Elemental mapping of the as-rolled sample #1 (Fig. 1b) also shows that Al and Cu elements diffused in opposite directions, and within the newly generated narrow diffusive layer, their concentration seemed to change in a continuous single step. Fig. 1(a) exhibit the selected-area diffraction patterns from both diffusive interface and constituent alloys of sample #1. The narrow diffusive interlayer can be indexed as the Al_4Cu_9 IMC phase. In specimen #3 processed for roll bonding with a reduction ratio of 50% (Fig. 1c), the Al layer contains a homogeneously elongated lamellar structure with several internal voids adjacent to the interface between parent alloys. However, in the Al/Cu laminated composite roll bonded under the lowest reduction ratio (30%), the Al layer microstructure mostly consisted of equiaxed sub-micrometer grains together with internal voids, which were not visible in the Al layer in sample #1. This clearly indicates that microstructural changes of both the parent alloy and the interface are strongly affected by the amount of shear strain induced by roll bonding, which is controlled in terms of the reduction ratio.

Table 1
Target reduction ratio and thickness of as-prepared Al/Cu two-ply laminated composites.

Al: heating (~380 °C) Cu: room temp.	Target reduction ratio, (%)	Final thickness of two-ply, (mm)
Sample # 1	65	3.05
Sample # 2	60	3.20
Sample # 3	50	3.21
Sample # 4	40	3.08
Sample # 5	30	2.80

The EBSD analysis data from samples #1, #3, and #5 are represented by image quality (IQ), inverse pole figure (IPF), and kernel average misorientation (KAM) maps in Fig. 2(a–c), respectively. The gray-scale maps in Fig. 2(a) correspond to the IQ. The Al part is darker than the Cu part due to its lower IQ value and higher lattice distortion. The grains in the Al part are bounded by low-angle grain boundaries (red and green lines), but in the Cu part, most of them are high-angle boundaries (yellow lines). As shown in Fig. 2(b), IPF maps can be represented in different colors, depending on the orientation of each point. In sample #1, grains in the IMC layer are refined and recrystallized by a high reduction ratio, and grain boundaries are high-angle boundaries (black lines). In samples #3 and #5, on the other hand, internal voids exist, as shown in TEM images (Fig. 1b and c), which interrupt the formation of the IMC layer, and there are no closed high-angle boundaries such as those in sample #1. Highly deformed and recrystallized areas in the microstructure typically indicate high local misorientation values [15]. For this purpose, we use the KAM maps that are constructed by calculation of every measurement point up to its second nearest neighbors (Fig. 2c). The yellow and green colors are used to represent higher residual strain, whereas blue is used to represent lower strain areas. Local misorientation areas are usually bounded by low and high-angle grain boundaries, and some areas are in the grain. KAM is generally higher in the Al part, and therefore, in the Al part, residual strain should be higher and more widely distributed than that in the Cu part. This seems to be caused by the fact that the strength of Al is lower and initial