



Microstructures and mechanical properties of Al/Zn composites prepared by accumulative roll bonding and heat treatment



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ABSTRACT

Al/Zn composites were fabricated using 1060-Al plates and Zn particles by accumulative roll bonding and heat treatment. X-ray diffraction analysis reveals that most of the Zn phase in the final Al/Zn composite disappeared in the Al matrix. Scanning electron microscopy and energy-dispersive X-ray spectroscopy analyses revealed excellent solid solution regions distribution in the final Al/Zn composite. The final Al/Zn composite showed higher hardness values of the solid solution regions than the Al matrix. Compared with ARBed monolithic 1060-Al, the Al/Zn composites had higher strength without sacrificing ductility. Crown Copyright © 2013 Published by Elsevier B.V. All rights reserved.

1. Introduction

Aluminum-based metal matrix composites (AMMCs) are attracting considerable attention. The traditional methods used to fabricate AMMCs include powder metallurgy [1], squeeze casting [2], pressureless infiltration [3] and spray forming [4].

Lu et al. [5] and Alizadeh and Paydar [6] produced AMMCs in 2009 by accumulative roll bonding (ARB) [7], a well-known severe plastic deformation (SPD) technique. Subsequently, several AMMCs such as Al/SnO₂ [8], Al/ZrO₂ [8], Al/Al₂O₃ [8–11], Al/B₄C [12,13], Al/SiC [8,14,15], Al/WC [16], Al/Cu [17,18], Al/W [19], Al/carbon fibres [20] and Al/intermetallic compounds [20,21] have been fabricated by this new method because of the resulting highly uniform reinforced particle distribution and potential economic efficiency. AMMCs are characterised by low density and high tensile strength but usually have low ductility at room temperature. AMMCs with high strength and good ductility are yet to be produced by ARB.

Compared with ARBed monolithic Al, ARBed AMMCs have lower ductility because of the presence of hard particles in the Al matrix. The reinforcing phases are non-plastic and always the preferential sites for crack nucleation during the tensile process. Insufficient bonding at the interface between the reinforcing phase and Al matrix results in a preferential crack propagation path that leads to plastic instability and the onset of necking.

In this paper, Al/10 wt%Zn composites were fabricated by ARB and heat treatment. The composites are reinforced by Al–Zn solid

solution regions. Unlike other ARBed AMMCs, the reinforcing phases in the final Al/Zn composites are also deformed during the tensile process; the preferential crack nucleation sites and crack propagation paths are eliminated; and ductility as well as strength can be achieved.

2. Experimental

2.1. Materials

The raw materials used were as-annealed 1060-Al sheets cut parallel to the sheet-rolling direction into 150 mm × 100 mm × 1 mm pieces, as well as Zn particles less than 4 μm in size. Table 1 presents the chemical composition of 1060-Al, and Fig. 1 shows the scanning electron microscopy (SEM) image of the Zn particles used.

Two pieces of the original 1060-Al sheets were degreased using acetone and then wire brushed. Subsequently, approximately 9 g of Zn particles were uniformly distributed between the two pieces of 1060-Al sheets using a scraper knife, and then the 1060-Al sheets were stacked together. The roll-bonding process was performed at room temperature without lubrication using a laboratory rolling mill 300 mm in diameter and 220 mm in barrel length. The rolling speed and rolling reduction were 0.1 m/s and 50%, respectively. Approximately 30 cm³ (81 g) of Al was used in the above process. Consequently, a composite with 10 wt% Zn particles was fabricated. To achieve uniform distribution of Zn in the Al matrix, the rolled composite was cut into two halves, and the above procedure was repeated to eight cycles without adding Zn particles (Step 1). The final sample is denoted as ARB_{step1} Al/Zn.

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Table 1
Chemical composition of the Al sheets used.

Element	Fe	Mg	Si	Zn	Ti	Cu	Al
Wt(%)	0.03	0.03	0.25	0.05	0.03	0.05	99.56

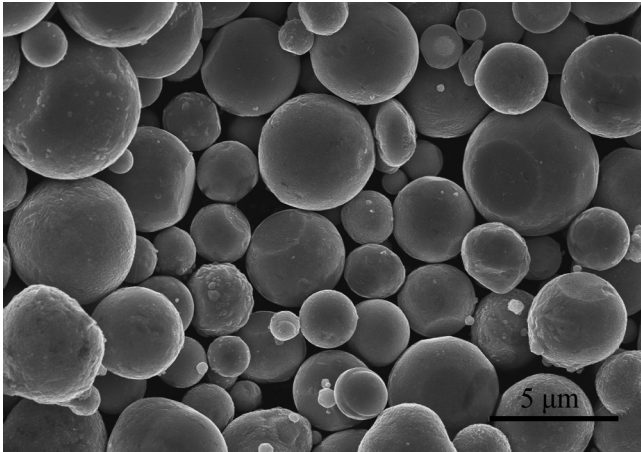


Fig. 1. SEM image of the Zn particles used.

ARB_{step1} Al/Zn was heated at 500 °C for 40 min in a tubular vacuum heat-treatment furnace under a vacuum atmosphere and subjected to rapid quenching in room-temperature water. The composite was subjected to three more cycles of ARB to introduce an ultrafine grained structure into the composite (Step 2). The final sample is denoted as ARB_{step2} Al/Zn.

2.2. Characterisation

The microstructures of the eight cycles of ARB monolithic 1060-Al (ARBed 1060-Al) and Al/Zn composites were examined by SEM and transmission electron microscopy (TEM). Energy-dispersive X-ray spectroscopy (EDX) was used to characterise the chemical component of the composites. X-ray diffraction (XRD) with Cu K α radiation was used to identify the phase composition of the composites.

Hardness measurements were conducted on the rolling direction–normal direction (RD–ND) plane of the annealed 1060-Al, ARBed 1060-Al and Al/Zn composites using a Vickers microhardness (HV) tester at 10 g for 10 s. The values are the average of 50 measurement points. The tensile samples were machined from the annealed 1060-Al, ARBed 1060-Al and Al/Zn composites with the tensile axis parallel to the rolling direction. Tensile tests were performed at a strain rate of $2 \times 10^{-4} \text{ s}^{-1}$ using an Instron-5982 type test machine, and stress–strain curves were then constructed. Fracture surfaces after the tensile tests were observed by SEM to determine the failure mode.

3. Results and discussion

3.1. Structural evaluation

The XRD pattern of the samples fabricated by a different process is shown in Fig. 2. Both Al and Zn are observed in the ARB_{step1} Al/Zn (B). After heat treatment, the intensity of Zn peaks decreases (C). The XRD results almost do not reveal the presence of the Zn phase, which means that most Zn atoms are dissolved in the Al lattice. The Al and Zn atoms diffuse together at 500 °C, and

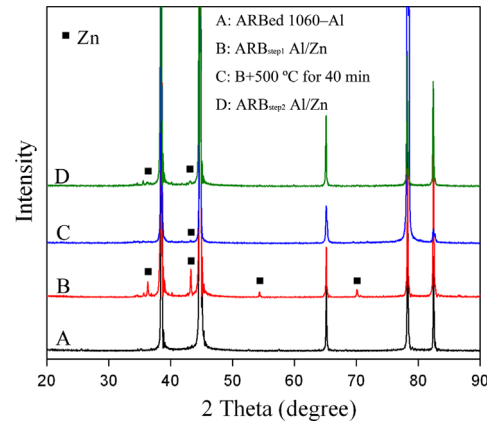


Fig. 2. XRD patterns of (A) ARBed 1060-Al, (B) ARB_{step1} Al/Zn, (C) ARB_{step1} Al/Zn subjected to heat treatment and (D) ARB_{step2} Al/Zn.

most Zn atoms are frozen in the Al matrix during the water-quenching process. Consequently, Al–Zn solid solution regions are formed. After the second ARB process, the intensity of Zn peaks slightly increases (D). Straumal et al. [22] reported that an SPD process such as high-pressure torsion leads to the decomposition of the supersaturated solid solution in Al–Zn alloys. In this study, some Zn atoms in the Al–Zn solid solution regions may also be rejected from the Al lattice during ARB. However, the Zn phase in ARB_{step2} Al/Zn is far less than that in ARB_{step1} Al/Zn. Fig. 2 also shows that the Al XRD peaks are not shifted in C and D. This phenomenon can be explained by the lower proportion of the Al–Zn solid solution region than that of the no-Zn atom region in the ARB_{step2} Al/Zn composite.

Fig. 3 shows the SEM images of the RD–ND plane of the Al/Zn composites. Unlike the microstructures of ARBed ceramic particle-reinforced AMMCs [5,6,8–16], a highly uniform reinforcing particle distribution is not observed in ARB_{step1} Al/Zn [Fig. 3(a)]. The soft Zn particles are deformed with the rolling process. Some Zn particles are bonded together, and a Zn layer is produced between the two layers of Al strips after the first roll-bonding process. Subsequent ARB induces the formation of Zn fragments consisting of Zn particles. After eight ARB cycles, a composite with homogeneously distributed Zn fragments parallel to the rolling direction is achieved. Similar to the ceramic particle-reinforced AMMCs, obvious interfaces exist between the second phase and Al matrix in the ARB_{step1} Al/Zn [Fig. 3(b)].

Fig. 3(c) shows that some fragments parallel to the rolling direction (white regions) also exist in ARB_{step2} Al/Zn. However, the width and length are significantly larger than those of ARB_{step1} Al/Zn. The colour difference in the SEM image of ARB_{step2} Al/Zn is considerably weaker than that shown in Fig. 3(a). The EDX analysis results along the scanning line in Fig. 3(c) are shown in Fig. 3(d). The white and grey regions in Fig. 3(c) correspond to the Zn-rich and Zn-poor regions, respectively. The elemental distribution trend has no strict steep, and the Zn elemental content gradually decreases from the centre of the Zn-rich regions to the Zn-poor regions. Thus, no obvious interfaces exist between the two regions.

Fig. 4 shows the TEM images of the RD–TD plane of annealed 1060-Al, ARBed 1060-Al and Al/Zn composites. Fig. 4(a) shows that the grain size of annealed 1060-Al is so large that a whole grain cannot be observed in the field of vision. Fig. 4(b) shows that the grain size of 1060-Al is finer and becomes 0.5 μm in diameter after eight cycles of ARB. ARB introduces an ultrafine-grained structure into 1060-Al.

Two phases are observed in the structure of ARB_{step1} Al/Zn, i.e., Zn particles appear black and Al grains appear grey [Fig. 4(c)]. Some of the initial spherical Zn particles become finer and

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