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A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes

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ABSTRACT

This paper focuses on some structural and mechanical characteristics of Al–Al_2O_3 composites produced by conventional accumulative roll-bonding (ARB) and cross accumulative roll-bonding (CARB). The obtained structures were studied by transmission electron microscopy, X-ray diffraction, and optical microscopy; typically, the reinforcement distribution on different orthogonal planes was quantitatively compared. Also, the composite samples were mechanically characterized by hardness, uniaxial tensile, and fractographic experiments. The results showed that the CARB process, compared with ARB, gives rise to somewhat more effective grain refinement. Concerning the particles dispersion, the lateral rolling planes of the CARB samples, contrary to those of the ARB composites, present a similar feature. It was also found that the hardness, yield stress, tensile strength, and elongation of the CRAB specimens are higher than those of the ARB composites.

1. Introduction

Aluminum metal–matrix composites (MMCs) are currently regarded as a group of advanced materials, due to lightweight, high strength, high specific modulus, low coefficient of thermal expansion, and good wear resistance, while a combination of these desirable properties can be hardly achieved by conventional materials. As reinforcing agents in MMCs, ceramic particles like Al_2O_3, SiC, B_4C, WC, and TiB_2 are generally used [1–5].

It is known that in order to get the optimum properties of a composite, especially a suitable combination of strength and ductility, a small size and large volume fraction of the reinforcement(s) are required. Nonetheless, there is a challenge of effectively and simultaneously taking advantage of these two requirements, since small reinforcing particulates in MMCs usually tend to be agglomerated and inhomogeneously distributed through the matrix. This unpleasant feature considerably degrades the mechanical behavior of the composite [6–8]. In this regard, it has been found that severe plastic deformation processes, for example high-pressure torsion [9], equal channel angular pressing [10], and accumulative roll-bonding [11–13] can successfully improve the homogeneity of the particulate reinforcement distribution in MMCs.

In the recent years, accumulative roll-bonding (ARB) has been increasingly used to produce MMC sheets [11–14]. In addition, a modification of the conventional ARB process, namely cross-accumulative roll-bonding (CARB), was introduced to prepare this type of materials [15], in which the strip is rotated 90° around the normal direction between successive passes. Concerning the reinforcement distribution in MMCs fabricated by ARB, it has been found that the homogeneity is improved by increasing the number of ARB passes [12]. Also, the structural homogeneity on the rolling direction–normal direction plane of ARB-processed MMCs has been reported to be better than that on the transverse direction–normal direction plane [16]. However, to our knowledge, no comparison of the reinforcement distribution has been made between ARB- and CARB-processed composites. In this paper, a comparative study is conducted on the structure and mechanical properties of Al–Al_2O_3 composites fabricated by ARB and CARB, especially on the alumina reinforcement distribution on the different plans of the processed sheets.

2. Experimental procedures

2.1. Materials and sample preparation

To fabricate Al–15 vol.% Al_2O_3 composites by ARB and CARB, strips of annealed 1050-aluminum alloy and Al_2O_3 powder with the average size of 3 μm was used as the raw materials.

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In the first step of the CARB process, the Al strips of 0.5 mm thickness were firstly degreased in acetone and scratch brushed. The eight surface-prepared strips were stacked each other, while 1.66 vol.% Al_2O_3 powder was dispersed at the seven interfaces of each two adjacent sheets. The product was roll-bonded with a reduction of 66% at room temperature. The well roll-bonded strip was cut into three strips and annealed at 623 K for 1 h. After the surface preparation and the dispersion of 1.66 vol.% Al_2O_3 powder between the two interfaces of each two adjacent sheets, the product was again roll-bonded with the same reduction. Then, the roll-bonded strip was cut into two strips and again annealed.

In the second step, the two obtained, surface-prepared strips were roll-bonded with a draft percentage of 50% reduction, without the alumina particles dispersion. The roll-bonded strip was cut into two strips; and after the surface treatment and without annealing, theses were stacked over each other and rotated 90° around the normal direction (ND) of the previous rolling pass. The rotated strip was roll-bonded with a draft percentage of 50% reduction. In fact, in this stage, the strip was rolled along the transverse direction (TD) of the prior stage. The last step of the process, i.e. cutting, surface preparation, rotation, and rolling, was repeated eight times. For comparison, Al–15 vol.% Al_2O_3 composites were produced by the ARB process, according to Ref. [14], where no strip rotation is conducted between successive passes.

2.2. Structural characterization

Transmission electron microscope (TEM) micrographs of thin foils parallel to the rolling plane (rolling direction–transverse direction or RD–TD plane), prepared by ion milling, were taken by a Philips, FEG-TEM operating at 200 kV. Additionally, the crystallite size of the matrix on the RD–TD plane surfaces of the ARB- and CARB-processed composites was determined by X-ray diffraction (XRD, D8 Bruker diffractometer, Cu Kα_1 radiation, λ = 0.15406 nm) peak profile analysis, using a step size of 0.03° and a counting time of 3 s per step. The MAUD software, which employs the Rietveld refinement and the Double-Voigt approach, was used to do so.

An optical microscope was used to observe the dispersion of the Al_2O_3 particles on the different planes of the MMCs, where the micrographs were analyzed by the radial distribution function. According to Refs. [12,17], in this quantitative analysis, circles of variable radii r, from 1 μm to 100 μm, were centered on a particle and the function $H(r)$ is then determined as below:

$$H(r) = \frac{N_{ra}}{N_a} \quad (1)$$

where N_{ra} is the mean number of the particles per unit area in the circles and N_a is the mean number of the particles per unit area over the whole sample. Afterwards, the degree of clustering (A_H) was estimated by the deviation of the $H(r)$ curves from $H(r)$ = 1 (as a random distribution of particles essentially yields $H(r)$ = 1 for any radius r), via the area described as follows:

$$A_H = \int_{r=1\ \mu m}^{r=100\ \mu m} [H(r) - 1]dr \quad (2)$$

where to obtain a reliable result, six particles were randomly selected as the central particle on the optical micrographs of the MMCs.

2.3. Mechanical experiments

Vickers bulk hardness tests, with a load of 150 g, were conducted on ten random locations of the produced MMCs. Also, uniaxial tensile tests were conducted on the MMCs by an Instron testing machine at an initial strain rate of $8.3 \times 10^{-4}\ s^{-1}$. The tensile test samples were machined from the ARBed strips oriented along the rolling direction, according to the 1/5 scale of the JIS-No. 5. Also, the fracture surfaces of tensile test specimens were evaluated by a scanning electron microscope (SEM, JEOL-JSM 6340F).

3. Results and discussion

3.1. Structural studies

The TEM micrographs of the ARB- and CARB-processed Al–Al_2O_3 MMCs after the eighth pass are shown in Fig. 1. According to these images, the mean grain size of the aluminum matrix in the ARB and CARB samples is almost 240 and 190 nm, respectively, while nanometric grains (smaller than 100 nm) can be also observed. Fig. 2 also indicates the XRD patterns of the MMCs processed by eight ARB and CARB cycles. According the XRD peak profile analysis using the MAUD software, the average crystallite size of the matrix in the ARB and CARB samples was determined to be almost 125 and 110 nm, respectively. Clearly, the crystallites detected by the X-ray line broadening analysis are smaller than the related grains observed by TEM, due to the sub-division of the grains into the substructures (crystallites).

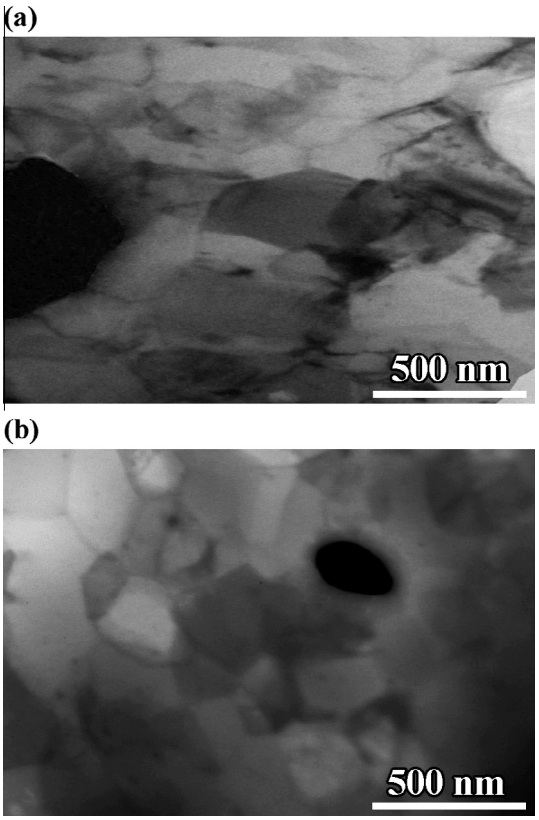

Fig. 1. TEM micrographs of the ARB (a) and CARB (b) composites processed to eight passes.

According to the TEM and XRD studies, the ARB and CARB processes to the eighth pass successfully develop ultrafine-grained, nanocrystalline Al–Al_2O_3 MMCs. Structural refinement can be explained in terms of grain sub-division at the submicron scale, due to severe plastic deformation [18,19]. Furthermore, the presence of the Al_2O_3 reinforcement particles in the aluminum matrix increases the dislocation density in the matrix during ARB and CARB. These dislocations are generated at the particles/matrix interface in order to accommodate the strain incompatibility between the two phases. On the other hand, the Al_2O_3 particles act as obstacles to the dislocation motion, thereby leading to the dislocation accumulation and to the formation of sub-grain and then grain boundaries. Moreover, the reinforcement particles retard the dislocation motion and dynamic recovery. Note that dynamic recovery retards grain refinement during ARB through dislocation annihilation, as especially reported for pure Al [20,21].

As it can be seen from the TEM studies, the matrix grain size in the CARB composite is less than that in the ARB sample. Essentially, there are two types of boundary in ARB structures, namely lamellar boundaries (LBs) which are almost parallel to the rolling plane and short transverse boundaries which interconnect LBs. During the CARB process, LBs alternately become parallel and perpendicular to RD in successive passes, due to the strip rotation around ND, as described in the experimental section. This leads the interconnecting boundaries spacing in the CARB sample to be less than that in the ARB sample. As a result, by employing the CARB process, the aspect ratio of the interconnecting boundary spacing and the lamellar boundary spacing is significantly reduced, which causes a more efficient grain refinement in comparison to ARB.