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A new consideration on reinforcement distribution in the different planes of nanostructured metal matrix composite sheets prepared by accumulative roll bonding (ARB)

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ABSTRACT

Recently, a number of novel methods based on accumulative roll bonding (ARB) have been introduced to produce particulate metal matrix composites. Nonetheless, the microstructure uniformity from the reinforcement distribution viewpoint in the different planes of ARBed composite sheets has not been focused up to date. This paper aims to compare the evolution of the B_4C particles distribution in nanostructured Al–10 vol.% B_4C composites prepared by ARB in the rolling direction–normal direction (RD–ND) and transverse direction–normal direction (TD–ND) planes. From optical microscopic evaluations quantified by the radial distribution function analysis, it is realized that the homogeneity in the RD–ND planes is in excess of the TD–ND planes. In addition, transmission electron microscopy reveals the development of nanostructures in the Al matrix after seven ARB passes.

1. Introduction

Aluminum matrix composites have attracted considerable attention, owing to lightweight, high strength, high specific modulus and good wear resistance. Boron carbide (B_4C) is a common ceramic reinforcement in metal matrix composites and presents considerable hardness, chemical resistance, and neutron absorbing properties [1–4]. Applications of Al–B_4C composites include its use as a structural neutron absorber, armor plate materials, and as a substrate material for computer hard disks [5,6].

To meet the optimum properties of a composite, especially the best combination of high strength and good ductility, the spatial distribution of reinforcement in metal matrix composites (MMCs) is one of the most important microstructural features, governed by the processing route. There are several methods to manufacture this type of composites, such as powder metallurgy, squeeze casting, pressureless infiltration, and spray forming. Recently, novel methods based on accumulative roll bonding (ARB) have been introduced to produce metal matrix composites. It has been reported that the B_4C reinforcement distribution in Al–B_4C composite fabricated by ARB is improved by increasing the number of ARB cycles [7]. However, up to date, the reinforcement distribution has not been compared in the different planes of the composite sheets (RD–ND and TD–ND planes). This paper focuses on the effect of the observation planes (RD–ND and TD–ND planes) on the evolution of the B_4C particles distribution in nanostructured Al–B_4C composites prepared by ARB via optical microscopy assessments.

2. Experimental procedure

Fully annealed 1050-aluminum strips and B_4C powders with a mean particle size of 2 μm were used as the raw materials. To produce Al–10 vol.% B_4C composites, the eight Al strips, which were degreased in acetone and scratch brushed, were stacked over each other, while 1.1 vol.% B_4C powders were dispersed between each pair of the strips. The strips were roll-bonded with a draft percentage of 66% reduction, in accordance with Ref. [8], at room temperature (Step 1). The roll-bonded strip was cut into three strips and annealed at 623 K for 1 h. After the surface preparation, the three strips were stacked, 1.1 vol.% B_4C powders were dispersed between them, and roll-bonded again (Step 2). The next stage of the production sequence was the ARB process. The roll-bonded strip obtained from Step 2 was cut into two strips and annealed. After the surface preparation, the two strips were stacked over each other (without dispersing the B_4C particles) and roll-bonded with a draft percentage of 50% reduction. This procedure was defined as one ARB cycle and repeated to seven times without annealing between each cycle. The rolling processes were carried out with the rolling speed of 15 rpm and the roll diameter of 150 mm, without any lubrication.

Transmission electron microscope (TEM, Philips-FEG) was used to observe the RD–TD plane of the composite ARBed to seven passes. The dispersion of the B_4C particles in the matrix in the RD–ND and TD–ND planes was evaluated by an optical microscope (OM). The optical micrographs were analyzed by the radial distribution function to quantify the reinforcement distribution [7]. In the radial distribution

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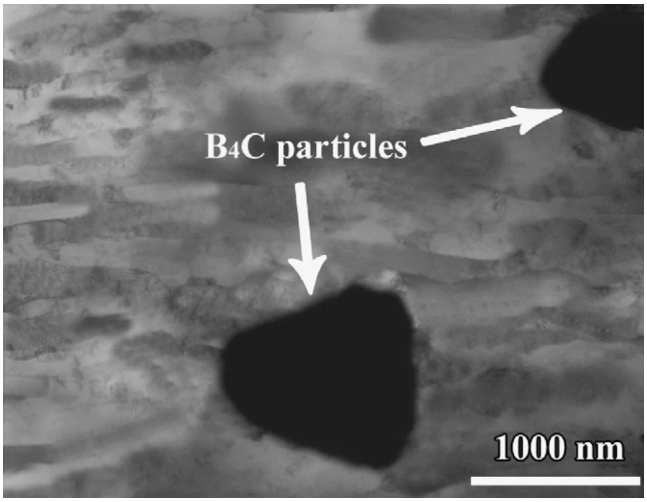

Fig. 1. TEM micrograph of the composite processed to seven ARB passes.

function, a circular disc of radius r is centered on the gravity center of a particle and the function $H(r)$ is determined as:

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

where N_{ra} is the mean number of the particles per unit area in a disc of radius r and N_a is the mean number of the particles per unit area over the whole sample. The degree of clustering is estimated by the deviation of the experimental $H(r)$ curves from $H(r)=1$ via the area A_H as described by:

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

To determine the radial distribution function, a range of radii from $r=1\ \mu$m to $r=100\ \mu$m was considered.

3. Results and discussion

The TEM micrograph of the composite processed by seven ARB passes is given in Fig. 1. As it can be seen, nanostructured grains elongated in RD have been developed in the Al matrix, where the average lamellar boundary spacing is about 110 nm, while the transverse boundary spacing is about 550 nm. Note that lamellar boundaries are almost parallel to RD and short transverse boundaries interconnect the lamellar boundaries. That is, the ARB process to seventh cycle has successfully developed a nanostructured Al–B_4C MMC. Structural refinement can be explained in terms of grain subdivision at a submicron scale, where initial coarse grains are subdivided by deformation-induced high-angle grain boundaries [9–11]. In addition, X-ray diffraction peak profile analysis depicted that the area weighted mean crystallite size of this sample is 114 nm [7]. Note that crystallites determined from the X-ray line broadening are smaller than the related grains observed by TEM, due to the subdivision of the grains into substructures. In other words, it should be considered that the crystallite size measured by the X-ray diffraction peak profile analysis corresponds to dislocation cells or subgrain sizes, where the variations of orientations are smaller than a few degrees.

The variation in the radial distribution function $H(r)$ can be employed to quantify the reinforcement distribution. In comparison to the Poisson pattern that reflects a homogeneous particle distribution, a random distribution of particles yields $H(r)=1$ for any disc radius r. On the other hand, the $H(r)$ curves for clustered distributions would show a sharp peak at small r values, rapidly dropping to a plateau of approximately 1 at larger r values [7]. The degree of clustering (A_H) for the TD–ND and RD–ND planes is presented in Fig. 2. Considering that larger A_H values are indicative

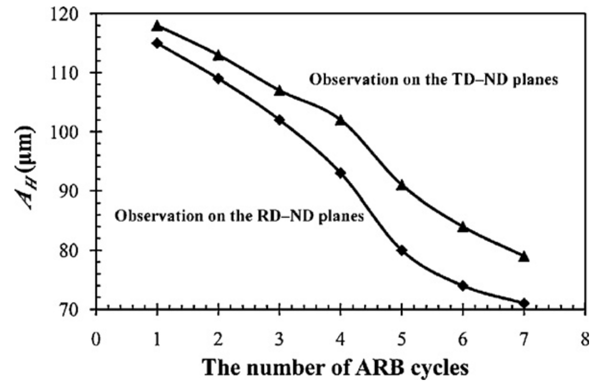

Fig. 2. Degree of clustering of the Al–B_4C composite produced by the ARB process in the TD–ND and RD–ND planes.

of increased particle inhomogeneity, it is inferred that by increasing the number of passes, an improvement in the microstructure uniformity is obtained, and the uniformity of the RD–ND planes is in excess of that of the TD–ND planes. Typically, Fig. 3 shows the optical micrograph of the TD–ND and RD–ND planes of the Al–B_4C composite processed to seven ARB passes, implying the better uniformity of the RD–ND plane.

The evolution of the B_4C reinforcement distribution is regarded from three viewpoints [7]: the increase in the number of the Al and B_4C layers, the metal extrusion through particle clusters, and the sheet elongation due to rolling. By progression of ARB, the number of the Al and B_4C layers is increased, dictating an improvement in

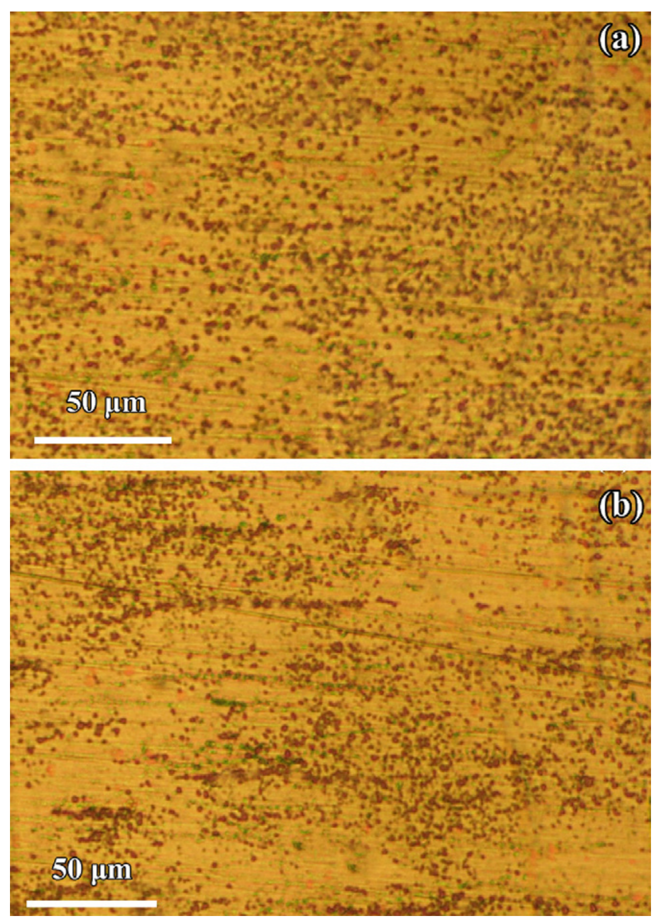

Fig. 3. Optical micrograph of the composite processed by the ARB process to seven passes in the RD–ND (a) and TD–ND (b) planes.

the particle distribution in ND. In addition, under the normal roll pressure, the matrix material is extruded and flows through B_4C particle clusters. As a result, dense particle clusters can be converted to diffuse clusters, and the distance between the particles constituting the clusters is enhanced, suggesting the dissociation of the clusters and the improvement of the reinforcement distribution. Furthermore, particle clusters are elongated in RD due to the sheet elongation, promoting the cluster expansion and the transition of dense-to-diffuse clusters, as accompanied by the matrix infusion between the particles. It means the increase of the distance of clusters' particles, the dissociation of clusters, the shrinkage of particle-free zones, and an improvement in the microstructure homogeneity. Dense particle clusters are denominated as particle agglomerations where no matrix material is present between the particles, while particle clusters with some amount of the matrix material between the particles are denominated as diffuse clusters.

It is clear that the mechanisms of the increase in the number of the Al and B_4C layers and the metal extrusion through particle clusters are active for both the TD–ND and the RD–ND planes. The difference is related to the mechanism of sheet elongation. During the rolling process, an amount of sheet elongation along RD, which is a function of the reduction level, occurs; on the other hand, the strain along TD can be logically supposed to be almost zero. Accordingly, the sheet elongation has no contribution to the particle distribution in the TD–ND plane, since no significant sheet elongation occurs along TD. Hence, the sheet elongation mechanism in the RD–ND planes provides a better uniformity than the TD–ND planes.

Considering the three mechanisms proposed for the improvement in the reinforcement distribution during ARB, it seems that cross accumulative roll bonding (CARB) process introduced by Alizadeh [12] to process MMCs provides a similar structure in the RD–ND and TD–ND planes form the reinforcement distribution viewpoint. It would be worth mentioning that in the CARB process, the strip is rotated 90° around the normal direction (ND) between successive passes, and RD in CARB is defined as the rolling direction of the first rolling pass.

4. Conclusions

This paper compared the evolution of the B_4C particles distribution in nanostructured Al–10 vol.% B_4C composites prepared by ARB in the RD–ND and TD–ND planes. From optical microscopic evaluations quantified by the radial distribution function analysis, it was realized that the homogeneity in the RD–ND planes is in excess of the TD–ND planes, due to the sheet elongation mechanism which is active along RD. In addition, transmission electron microscopy reveals the development of nanostructures in the Al matrix after seven ARB passes.

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