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Processing of ultrafine-grained aluminum by cross accumulative roll-bonding

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ABSTRACT

In this paper, the structural and mechanical characteristics of aluminum strips subjected to two severe plastic deformation processes, namely accumulative roll bonding (ARB) and cross accumulative roll bonding (CARB), are compared. Transmission electron microscopy studies on the strips showed that ultrafine grains are formed by both of the processing routes to eight passes. However, the structure of the CARB-processed specimen was less elongated than that of the ARB-processed specimens; that is, the aspect ratio of grains in the CARB case was less than that in the ARB specimens. Tensile tests indicated that the tensile strength is increased with the number of rolling passes, and the strength of the CARB specimens is higher than that of the ARB specimens.

1. Introduction

Polycrystals having small grains with an average size of 100 nm–1 μm are identified as ultrafine-grained (UFG) materials. Compared to conventional coarse-grained structures, UFG materials present some outstanding properties such as high strength, low-temperature and/or high-strain-rate superplasticity, enhanced fatigue behavior, and superior corrosion resistance [1,2]. These desirable features have caused UFG materials to attract a lot of interest in the recent years. Deformation to large strains below the recrystallization temperature without intermediate heat treatments, named as severe plastic deformation (SPD), can result in UFG structures [1,2]. Several SPD techniques, such as equal-channel angular pressing, high-pressure torsion, and accumulative roll-bonding (ARB) [3,4] have been developed to fabricate UFG materials.

In the ARB process, the surfaces of the strips to be joined are cleaned, roughened (by scratch brushing), and then stacked. After stacking, the specimen is bounded by rolling, is cut into two specimens, and the above-mentioned procedure is repeated several times. It has been shown that the repetition of the ARB process, typically above five passes, can develop a pancake shaped or elongated lamellar UFG structure in various metallic materials. The formation mechanism of UFG structures by ARB is explained in terms of grain subdivision at the submicron scale [3–9].

In order to extend the applications of ARB materials, reproducibility and reliability in their mechanical properties are some of the critical challenges. Since the microstructure determines the mechanical properties, the reliability in the mechanical properties depends on structural features like homogeneity and morphology. There are several reports in the literature on the microstructure homogeneity in UFG materials fabricated by SPD [10–12]. Recently, Kamikawa et al. [13] showed that the structure of ARB-processed ultralow-carbon IF steel without lubrication is macroscopically heterogeneous. In addition, a considerable local variation in the morphology of microstructure and in boundary populations has been observed in ECAP-processed copper and commercially-pure aluminum [14].

Recently, a novel method based on the ARB process was introduced to fabricate nanostructured Al/B_4C composite sheets [15]. This method, which was named as the cross accumulative roll bonding (CARB) process, can potentially affect the morphologies of the specimen microstructure. This work aims to compare the microstructure and mechanical properties of UFG aluminum specimens prepared by ARB and CARB.

2. Experimental procedures

2.1. Sample preparation

Aluminum 1100 alloy strips, annealed at 623 K, with the length of 200 mm, the width of 200 mm, and the thickness of 1 mm were used as the raw material. The strips were degreased in acetone and

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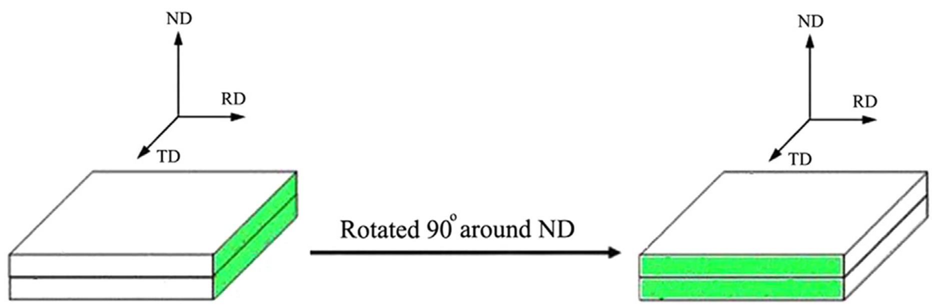

Fig. 1. Schematic illustration of the strip rotation around the ND in the CARB process.

scratch brushed at first. To process by CARB, two strips were stacked over each other and roll-bonded with a draft percentage of 50% reduction at room temperature. The roll-bonded strip was cut into two strips and after degreasing and brushing, they were stacked over each other and rotated 90° around the normal direction (ND) axis (see Fig. 1). The rotated strip was roll-bonded with a draft percentage of 50% reduction again. In fact, in this step, the strip was roll-bonded along the transverse direction (TD) of the prior stage. The last step of the process was repeated to eight passes without annealing between each pass. For comparison, the strips were produced by the ARB process, without any rotation between successive passes.

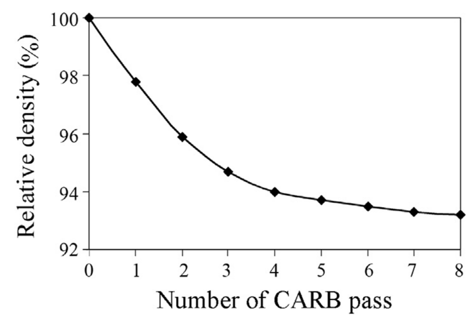

Fig. 2. Relative density of the strips produced by the CARB process.

2.2. Sample characterization

The density of the specimens was measured by the Archimedes water immersion method. To evaluate the bonding condition of the processed sheets, the optical microscopy examination of the samples was conducted. All of the optical microstructures were obtained from the rolling direction–normal direction plane of the samples. A scanning electron microscope (SEM, JEOL-JSM 6340F) was also used to observe the microstructure of the as-received material. The grain structure of the ARB- and CARB-processed samples was also evaluated by a transmission electron microscope (TEM, Philips-FEG, operating at 200 kV). To do so, thin foils parallel to the rolling direction (rolling direction–normal direction or RD–ND plane) were prepared by the twin-jet polishing technique using a solution of 400 ml HNO_3 and 800 ml CH_4OH.

Tensile test specimens were machined from the rolled sheets, according to the 1/5 scale of the JIS-No. 5 specimen, oriented along the rolling direction. The gauge length and width of the tensile test specimens were 10 and 5 mm, respectively. The tensile tests were carried out at an ambient temperature and at a nominal strain rate of $8.3 \times 10^{-4}\,s^{-1}$ by an Instron tensile testing machine. The total elongation of the specimens was also measured from the difference in the gage length before and after testing.

3. Results and discussion

The relative density of the CARB-processed strips vs. the number of the CARB pass is shown in Fig. 2, where the relative densities were calculated relative to the density of the as-received sheet. The observed decreasing trend is attributed to the increase in the level of discontinuities, due to the increase in the number of the strip interfaces and thereby unbonded points by increasing the CARB pass. On the contrary, it has been reported that for CARB-processed Al-B_4C composites, the relative density is enhanced by increasing CARB passes [16]. This difference suggests that in the latter case, compared to the metallic aluminum samples, the improvement in the reinforcement distribution uniformity (leading to the decrease in structural defects inside particle clusters) prevails over the increase in the number of the sheet interfaces.

Fig. 3 shows the typical optical images of the RD–ND planes of the CARB-processed aluminum sheets at one, five, and eight passes, where the last interfaces are indicated by arrows. It can be seen that, in the first rolling passes, the interface of the strips (Al strip/Al strip) is completely visible, since the welding efficiency is low and consequently the level of unbounded interfaces is high. Therefore, the density of the strip at the first pass is lower than that of the as-received strip. By increasing the rolling passes, new interfaces are introduced into the sample, thereby decreasing the density. However, it is noticeable that by progression of the process, the weld efficiency of the previous interfaces is increased and discontinuities are decreased, so that the interfaces, except the last interfaces, will become almost invisible. Typically, after eight passes, 2^{8-1} interfaces are produced; however, only a few unbonded parts of interface are seen in this specimen (Fig. 3c). Indeed, as pointed out in Ref. [17], the radial pressure and the tangential shear stress of rolling allow the material to flow in a different direction, thereby improving the bonding quality of interfaces introduced in the previous passes.

The TEM micrographs and corresponding selected area diffraction (SAD) patterns taken from the RD–ND planes of the ARB- and CARB-processed specimens of the eighth pass are shown in Fig. 4. As can be seen, the structure of the annealed strips is changed from an initial state of equiaxed grains, with an average size of about 9 μm determined by the intercept method (Fig. 5), into a final state of pancake-shaped, ultrafine grains aligned in the RD. According to Refs. [3–8,18], a typical dislocation cellular structure is created in initial passes. The structure at this stage contains a mixture of deformed and non-deformed grains with some dislocation tangles, since plastic deformation is inherently inhomogeneous at the microscopic level. By increasing ARB passes, the dislocation density is increased and the cell size becomes finer, leading to ultrafine subgrains divided by dislocation walls. The fraction of the ultrafine grains is increased by increasing ARB passes, so that in final passes the specimen is filled with ultrafine