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Effect of differential speed rolling strain on microstructure and mechanical properties of nanostructured 5052 Al alloy

Loorentz, Young Gun Ko *

School of Materials Science and Engineering, Yeungnam University, Gyeongsan 712-749, South Korea

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ABSTRACT

The present work reported the influence of differential speed rolling (DSR) strain on microstructure and mechanical properties of the nanostructured 5052 Al alloy. As the amount of DSR strain increased, the deformed microstructure developed from the band-like structure of the elongated grains after one-pass DSR (≈0.4) into the nanostructure of the equiaxed grains whose mean size of ≈700 nm after four-pass DSR (≈1.6). This was attributed to the fact that, by a sample rotation of 180° along the longitudinal axis, the macro shear deformation formed by one-pass DSR was intersected with that by two-pass DSR. From the microhardness contour maps of the DSR-deformed samples, the microhardness values and their uniformity were improved with increasing amount of DSR strain. Tensile test results showed that, as the amount of DSR strain increased, the tensile strength increased significantly while sacrificing tensile ductility and strain hardenability. Such mechanical response of the nanostructured 5052 Al alloy was discussed in relation to microstructure evolution during DSR.

1. Introduction

The processing of bulk metallic metals by means of severe plastic deformation (SPD) techniques has been generating great interest in recent years because the nanostructured materials fabricated via SPD methods, such as high pressure torsion (HPT) and equal channel angular pressing (ECAP) possessed superior mechanical properties to their coarse grained counterparts [1–6]. Asymmetrical rolling was one of the continuous SPD techniques suitable for achieving severe grain reduction below the micrometer level, together with a deep industrial potential. Among asymmetrical rolling methods, a differential speed rolling (DSR) was known to be desirable for enhancing the mechanical properties of the workpieces. DSR was one of the rolling methods utilizing two identical rolls in size where each was driven by its own motor, generating the different rotation speeds of upper and lower rolls, so that the shear strain could be imposed uniformly through the sheet [7,8].

In this regard, active research endeavors have been made recently, and successful applications have been reported for various materials such as Fe [9,10], Al [11,12], Ti [13,14], etc. For instance, Jiang et al. [11] demonstrated the use of DSR method resulted in severely refined grains of pure Al. Kim et al. [13] reported that the excellent combination of ultrafine grained structure and high tensile properties of commercially-pure Ti was attained by controlling the speed ratio and deformation temperature during DSR. Despite these previous investigations, however, a systematic study on how DSR strain influences microstructure evolution and mechanical properties of Al alloy will be needed. Therefore, the main purpose of the present work is to study the effect of amount of strain on microstructural development of Al alloy fabricated via DSR. The mechanical properties of the DSR-deformed Al alloy samples are also investigated.

2. Experimental procedures

The material used in this study was a 5052 Al alloy sheet with a chemical composition of 2.2 Mg, 0.2 Cr, 0.4 Fe, 0.25 Si, 0.028 Ti and the balance Al in wt.%. The as-received microstructure was homogenized at 823 K for 30 min followed by air cooling, resulting in a coarse grained microstructure whose grain size was ≈95 μm as shown in Fig. 1(a). Prior to DSR, the sample was machined into the plate type with a dimension of 70 × 30 × 4 mm. The principle and direction of DSR operation were depicted in Fig. 1(b). The diameters of the two rolls in DSR equipment were identical as 220 mm. The DSR processing was performed at a roll speed ratio of 1:4 for the lower and upper rolls, respectively, while the velocity of the lower roll was fixed at ≈3.4 m/min. The sample was subjected to four-pass DSR operations with a height reduction of 30% for each pass, corresponding to the total strain of ≈1.6. Each sample was rotated 180° around its longitudinal axis between passes.

Poulton's reagent was used to etch the sample for optical observation. For transmission electron microscope (TEM) observations, the thin foils were cut from the normal direction (ND)-rolling direction (RD) plane of the deformed samples where the effect of shear deformation on microstructure evolution was clearly shown as reported earlier [15]. TEM micrograph and corresponding selected area electron diffraction (SAED) pattern were taken by using TEM (Hitachi H-7600) operating at 120 kV. Vickers microhardness tests were conducted on the ND-RD plane of the DSR-deformed samples with a load of 100 g and a dwelling time of 10 s. A series of individual results obtained from the polished sections with a gap of ≈0.2 mm were recorded. These values were then plotted in the form of the contours depicting

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* Corresponding author. Tel.: +82 53 810 2537; fax: +82 53 810 4628.
E-mail address: younggun@ynu.ac.kr (Y.G. Ko).

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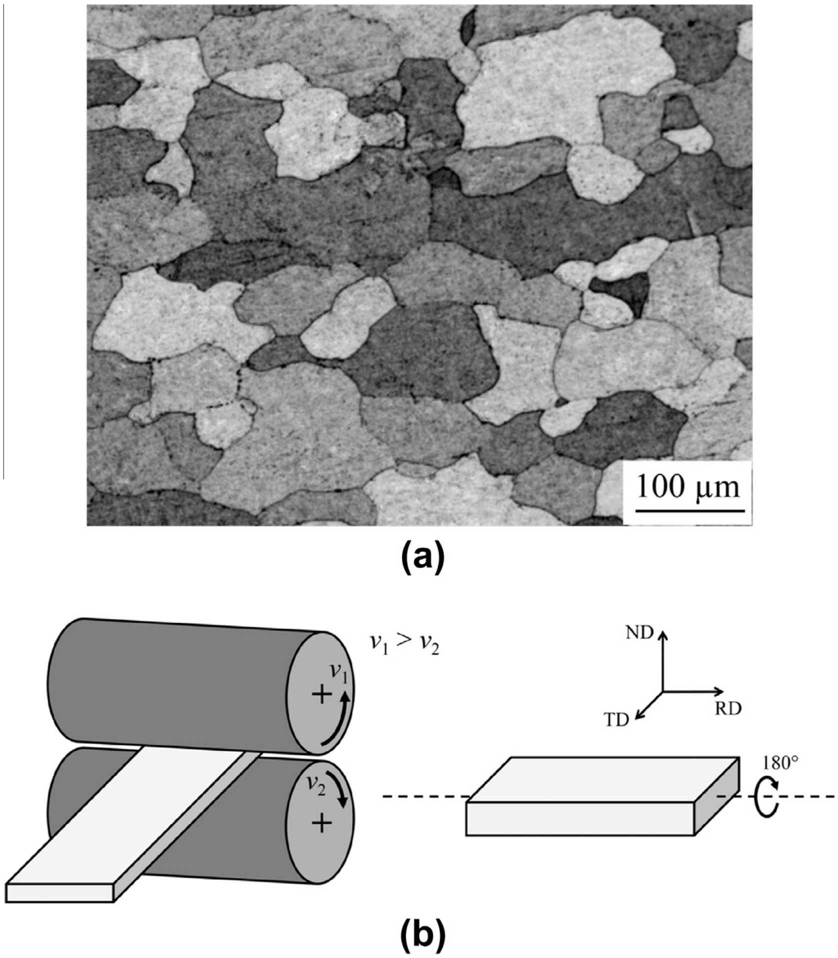

Fig. 1. (a) Initial microstructure of 5052 Al alloy and (b) schematic illustration of DSR machine and sample rotation method.

the distribution of the microhardness over the ND-RD plane of samples. Tensile test was performed at room temperature on the dog-bone sample with a gauge length of 25 mm and a width of 6 mm at a constant rate of crosshead displacement with an initial strain rate of 10^{-3}/s.

3. Results and discussion

3.1. Microstructure

Fig. 2 shows the optical micrographs taken from the ND-RD plane of the DSR-deformed samples as a function of DSR strain. In spite of the high roll speed ratio of 1:4 used in this study, no obvious plastic failure of the samples such as surface crack and wrinkle was detected with increasing DSR operations, which was responsible for the excellent cold-workability of 5052 Al alloy. As apparent from Fig. 2(a), the microstructure developed into the coarse elongated grains parallel to the DSR deformation direction after one-pass DSR, leading to the band-like structure with a thickness of ≈40 μm. As the amount of DSR strain increased, the microstructural observation shown in Fig. 2(b)–(d) revealed that the thickness of the band structures became slender and the contour of the band boundaries was likely to be indistinct due to high amount of DSR strain. A similar trend was also found in the previous study [7].

To figure out the details of microstructural features, the bright-field TEM and SAED pattern images of the deformed samples are shown in Fig. 3. The deformed microstructures tended to vary with respects to observing area and DSR strain. After one- and two-pass DSR operations, the microstructure evolution was observed to be gradual from top to bottom regions. As the amount of DSR strain increased, however, the microstructure tended to be reasonably uniform. Thus, TEM images which were obtained from the middle region of the sample were displayed in Fig. 3. since the middle region represented the whole deformed microstructure. After one-pass DSR, the microstructure was mainly comprised of fine lamellar bands of elongated subgrains with a width of ≈1 μm. Due to the low-angle misorientation of the band boundaries in nature which was confirmed by the individual regular spots in the SAED pattern, they seemed to be invisible through optical observation. Thus, the amount of strain imposed by a single DSR was insufficient to induce the formation of nanostructure having the high misorientation. Numerous dislocations were mainly detected in the vicinity of subgrain boundaries while the dislocation density was comparatively low in the matrix. As shown in Fig. 3(b), the microstructure after two-pass DSR showed the equiaxed subgrains whose size was comparable to the width of lamellar bands fabricated by one-pass (≈1 μm). The SADP spots of the deformed sample were diffused, suggesting the fact that a misorientation difference between subgrains begun to increase without a significant further reduction in grain size in order to accommodate the intense plastic strain. In Fig. 3(c), it was observed that the elongated grains appeared after three-pass DSR, which was similar to that after a single pass in terms of grain morphologies, but both the width and length of the elongated grains became smaller. By four-pass DSR (Fig. 3(d)), the deformed microstructure was consisted of nearly equiaxed nanostructured grains of ≈0.7 μm, which were