Journal of Alloys and Compounds 509 (2011) 3806–3810

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Shear banding phenomenon during severe plastic deformation of an AZ31 magnesium alloy

S.M. Fatemi-Varzaneh[a,*], A. Zarei-Hanzaki[a], J.M. Cabrera[b,c]

[a] Department of Metallurgical & Materials Engineering, University of Tehran, Iran
[b] Departamento de Ciencia de Materiales e Ingeniería Metalúrgica, ETSEIB, Polytecnic University of Catalonia, Av. Diagonal 647, 08028 Barcelona, Spain
[c] Centro Tecnológico CTM, Av. Bases de Manresa 1, 08242 Manresa, Spain

ARTICLE INFO

Article history:
Received 9 September 2010
Received in revised form 2 January 2011
Accepted 3 January 2011
Available online 5 January 2011

Keywords:
SPD
AZ31
ABE
Shear band

ABSTRACT

Severe plastic deformation was applied on a wrought AZ31 magnesium alloy by a new method called accumulative back extrusion (ABE). Instabilities of plastic flow in the form of localized shear bands were experimentally observed during ABE processing of the AZ31 alloy. The obtained microstructures show the appearance of shear bands in ABE processed specimens, the extent of which was observed to be decreased by increasing the temperature. The restricted flow (due to the deformation geometry) was discussed as the main cause of the latter behavior. A noticeable grain refinement was observed inside the shear bands which was attributed to the occurrence of continuous dynamic recrystallization inside the bands. To analyze the homogeneity of mechanical properties, the microhardness variations from the deformed bulk to the shear bands were measured and interpreted. The role of shear banding in grain refinement with no harmful effect on material soundness was explained.

1. Introduction

Mg alloys have many potential applications because of their low density and good machinability, but as a consequence of their hcp structure, they generally exhibit only limited ductility at low temperatures. One of the promising methods to increase ductility and strength in Mg is through microstructural refinement. It is well established that the processing of metals through the application of severe plastic deformation (SPD) is very effective in producing significant grain refinement with the as-processed microstructures having grain sizes typically lying within the sub-micrometer or even the nanometer range [1]. Having a limited number of slip systems, the magnesium alloys lay within the range of the so-called difficult-to-work alloys. Experiments have shown the development of segmentation or cracking in these alloys during SPD [2]. To achieve a successful processing by SPD processes a strategy is increasing the processing temperature. For magnesium alloys, several studies have shown that the SPD operation becomes easier if deformation is conducted at elevated temperatures [3]. In practice, however, an increase in the processing temperature leads to an increase in the as processed grain size [4] and accordingly it is preferable to conduct SPD at the lowest temperature consistent with an absence of any significant cracking in the billets.

In the case of equal channel angular pressing (ECAP), if appropriate facilities are available, the pressing operation becomes easier when using a die equipped with a back-pressure facility [3]. It has been recognized that the AZ31 billets became cracked when ECAP was conducted without a back-pressure at lower temperatures [5]. As the most common wrought magnesium, AZ31 alloy was successfully deformed by one pass ECAP at temperatures as low as 100 °C with the application of a moderate back pressure [4], though they reported a failure at 100 °C after two passes. The introduction of a 50 MPa back-pressure permits processing by ECAP at low temperatures as Langdon et al.'s work [3], where pressing was continued successfully for up to eight passes at 150 °C. The latter resulted in producing an ultra fine grain structure having a mean grain size of 0.8 μm. However, Kim et al. [6] failed in producing ZK60 samples without surface cracks at temperature of 250 °C. The SPD of magnesium alloy at low temperatures is yet under investigation to explore any possible way to produce sound materials.

It has been shown relying on macroscopic and microscopic observations that fracture of AZ31 alloy during ECAP is controlled by flow localization preceding fracture [7]. Observations of shear banding were interpreted in terms of the tendency for strain concentration as quantified by normalized flow softening. Similarly, Huang et al. has discussed that the shear bands may exhibit a favoured crystalline orientation for localization and cracking via shearing fracture [8]. The phenomenon of shear banding during severe deformation of magnesium alloy is not well understood.

Recently, an accumulative back extrusion method (ABE) has been invented as a new continuous SPD process suitable for mass

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[*] Corresponding author. Tel.: +98 2161114167; fax: +98 2188006076.
E-mail address: mfatemi@ut.ac.ir (S.M. Fatemi-Varzaneh).

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doi:10.1016/j.jallcom.2011.01.019

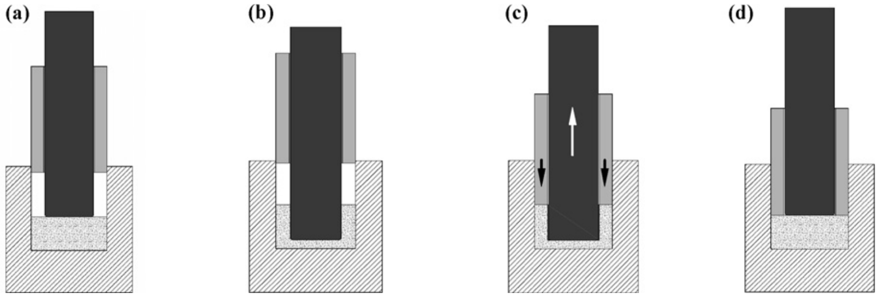

Fig. 1. The schematic illustration of accumulative back extrusion (ABE) processing.

production by one of present authors [9]. In this study low temperature severe plastic deformation (SPD) of an AZ31 magnesium alloy was dealt with using ABE method. The microstructural evolutions during severe deformation including shear banding phenomenon was focused and discussed. Our results may assist to shed light on shear banding behavior of magnesium alloy at low temperatures.

2. Experimental procedure

2.1. Deformation method

The principle of the ABE technique is illustrated in Fig. 1. In the first step the work piece is located into the die cavity (Fig. 1a). Any cycle of accumulative back extrusion consists of a back extrusion followed by a two-dimensional constrained back-pressing. These are being performed through an innovatively designed twin punch setup. The punches are designed to slide through each other. In the first step the work piece is extruded into the gap between the inner punch and the die through the back extrusion process (Fig. 1b). In the second step the back extruded material is forged back by the outer punch (as a hollow ram, Fig. 1c). As the outer punch is being pushed down, the inner punch is loosely lifted up by the undergoing material flow. The latter causes the deformation continues without any reduction in work piece cross section. Moreover, the inner punch is remained inside the cup during the second step thereby preventing from the cup to collapse or buckle inward. Consequently at the end of any cycle the initial shape of the work piece is reproduced (Fig. 1d). As a work-piece is processed by an ABE cycle, it is constrained to deform by shear strain, where an equivalent strain values of 4–5 may be imposed [10].

2.2. Material and characterization method

A commercial AZ31 alloy (Mg–3Al–0.9Zn–0.7Mn, wt%) was received in the form of as-rolled plates of 22 mm thickness. The cylindrical testing specimens were cut with diameter of 18 mm and height of 8 mm, the deformation axis of which selected to be parallel to the initial rolling direction. ABE was conducted at a ram speed of 10 mm/min and temperature of 80 and 130 °C. Experimental results obtained at higher temperatures up to 430 °C were presented elsewhere [11]. The die was preheated to and stabilized at deformation temperature before processing. Graphite spray was used to reduce the friction between the work piece and the tools surfaces. The specimens for microstructural observations were cut parallel to their longitudinal axis. The resulted microstructures were examined through standard metallographic procedures.

3. Results and discussion

Fig. 2 shows optical micrographs of the as-received AZ31 alloy, where equiaxed grains are homogeneously distributed with an average grain size of 25 μm. The typical microstructure of the experimental alloy, deformed by the first step of ABE cycle at temperatures of 80 and 130 °C is shown in Fig. 3 According to the obtained microstructures, a bimodal structures including both of deformed grains and shear bands may be realized (arrowed in Fig. 3). The shear bands formed along the deformation channel and mimicked the shearing pattern [11], which are dark due to the refined grains.

Strain localization in the form of shear bands, i.e. narrow regions of concentrated plastic flow, is an important mode of inhomogeneous deformation. When the strain begins to concentrate during deformation, the sites of localization are generally taken to be the position of greatest weakness within the specimen. The most common causes of weakness are variations in grain orientation (texture), grain size and precipitate fineness [12]. The mode of flow localization due to flow softening varies depending on the deformation state or strain path followed. Under condition of plain-strain loading the localization is free to become more concentrated, leading to the formation of shear bands. The main cause of flow softening in shear bands at high temperature has been described to be dynamic recovery, recrystallization and the reversal effect of strengthening mechanisms [12]. Moreover, in hexagonal material the proportion of flow softening that can be produced by texture modification may be noticeable [12].

The phenomenon of shear banding becomes a particularly important issue in severe plastic deformation processing, such as ECAP [2] of low-ductility materials [13], as in these processes crack initiation and failure of the billet occur along the shear bands formed. In the case of magnesium alloy it has been reported that the fracture of the specimens can be accompanied by shear banding at high strain rates [14]. Also the appearance of shear bands was observed by Lapovok et al. [15] during ECAP of AZ31 magnesium alloy. Moreover, the non-detrimental pronounced role of shear banding in developing a random recrystallization texture was also discussed during accumulative roll bonding (ARB) [16]. In the present work and for the ABE technique, also the appearance of micro-shear bands was found. The deformation temperatures employed in this work, are well below the activation temperature of non-basal slip in Mg, although those imply homologous temperatures of 0.38 and 0.43. Below 200 °C, twinning is the dominant deformation mechanism in magnesium alloys [17], so that frequent twinning bands can be seen in the microstructure at early stages of deformation (see Fig. 4a). Moreover, some new grains nucleated in grain boundaries may be observed.

Due to an insufficient number of operative slip and twinning systems, magnesium has a poor hardenability and limited ductil-

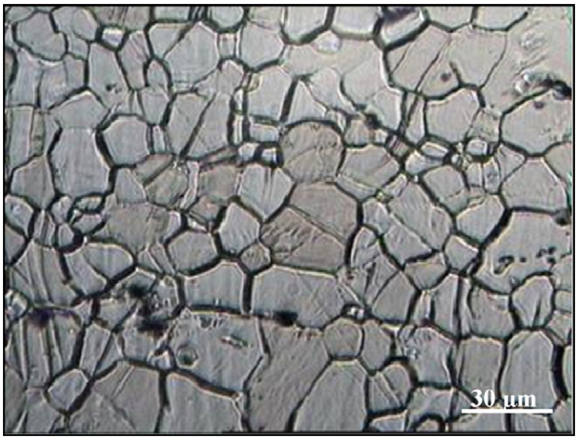

Fig. 2. The initial microstructure of AZ31 alloy used in this work.

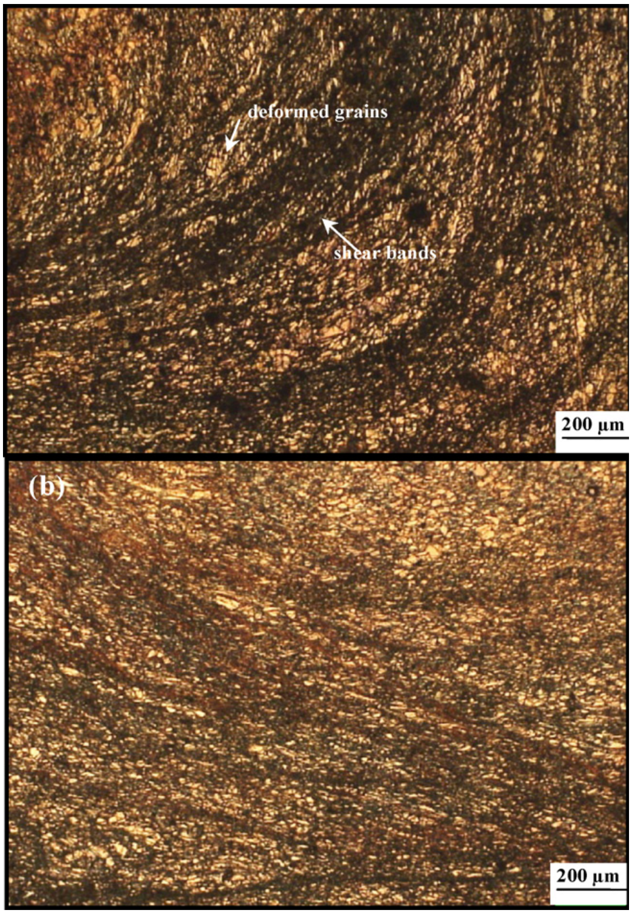

Fig. 3. Optical micrographs of the experimental alloy deformed through first step of ABE cycle at (a) 80 °C and (b) 130 °C.

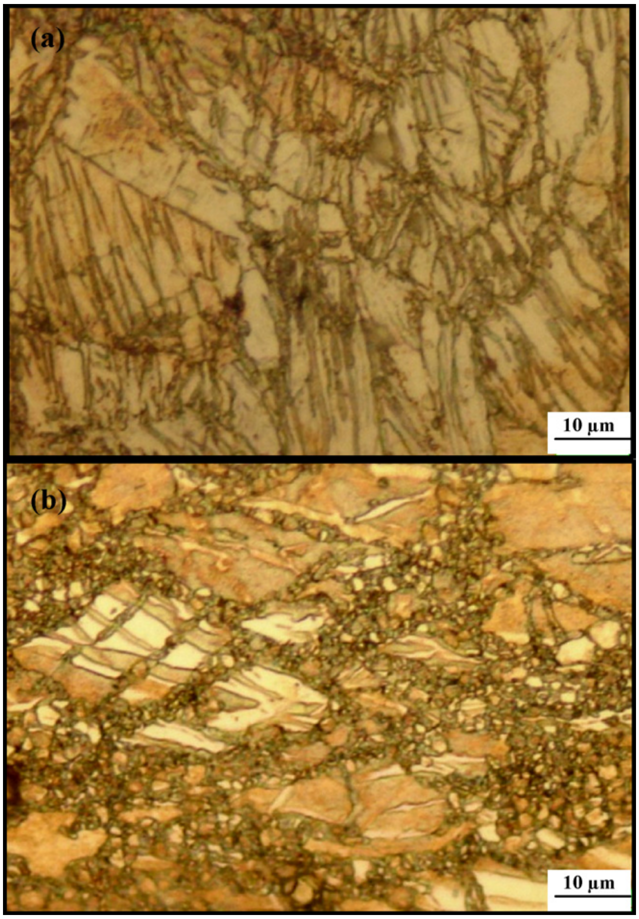

Fig. 4. Optical micrographs of AZ31 alloy deformed at 130 °C showing (a) twinning dominant flow at early stage and (b) DRX ending up to the shear band nucleation.

ity at low temperatures. Agnew and Duygulu [18] have reported a minimal constant strain hardening rate of 0.12 below 200 °C. Since ABE process is associated with a high magnitude of shear strain [10] the experimental alloy is not hardenable enough to embed the applied strain. Therefore the continuous flow cannot be established and consequently the deformation follows in narrow regions of internally localized plastic flow crossing many grains. The flow localization in the form of shear bands may occur as fallows. As the deformation progresses and higher strain values are imposed, the grains the orientation of which favours for twinning tend to be partly reoriented. The latter may occur in a way that basal slip can be easily activated. The latter was well-documented in previous studies [17]. In such grains, the intersection of twinning bands and grain boundaries and also the higher activity of slip systems may result in more nucleation of new grains, i.e. dynamic recrystallization (DRX). Since DRX leads to the annihilation of dislocation on a massive scale, this allows deformation to occur preferentially within the new grains, i.e. nucleation of localized flow. This stage may be realized in Fig. 4b. If the shear band reaches to regions with no work hardenability (i.e. not favourite for twining), it may continue to be extended by making a bridge to sites of new grains. The shearing deformation introduced by ABE actually achieved inside the shear bands. It should be noted that these observed bands in an isotropic material originate from plastic instability imposed due to the constraints of deformation. The latter should be differentiated from "ductile shear zones" observed and explained by Ion et al. [19] and del Valle et al. [20]. Ion et al. [19] observed band formation in a dilute Mg–Al alloy after hot compression tests. They suggested that the bands form as a consequence of rotation dynamic recrystallization during hot working. The operation of non-basal systems in newly formed grains may give rise to rotated regions at the vicinity of grain boundaries, accommodating the imposed deformation. The recrystallized grains tend to cluster in the form of large banded area called "ductile shear zone". Similarly, the formations of "ductile shear zones" was taken into consideration by del Valle et al. [20] to explain microstructural evolution of AZ61 magnesium alloy during large-strain rolling.

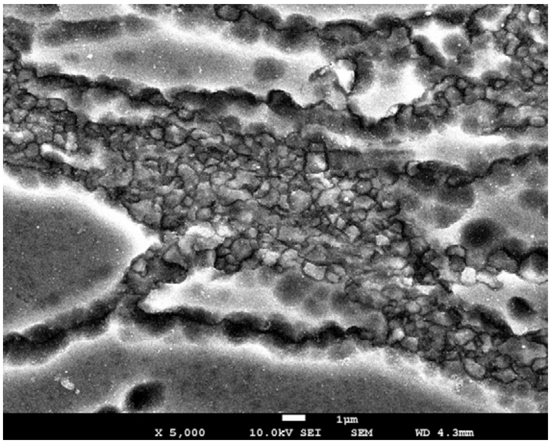

Fig. 5. Noticeable grain refinement inside the shear band, formed during first step of ABE at 130 °C.

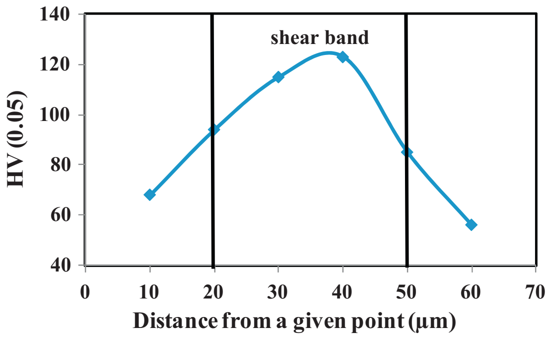

Fig. 6. Microhardness variation profile measured at shear banding region.

As seen in Fig. 3 the appearance of shear bands in samples tested at 130 °C is less extended. This may be attributed to progress of dynamic recrystallization which is more pronounced at higher temperature [21], and therefore the structural homogeneity may be promoted.

According to Fig. 5, outstanding grain refining may be realized in the shear bands. The shearing deformation actually achieved inside a shear band is extremely large [22]. This may promote a high density of dislocations followed by continuous dynamic recrystallization. The latter may end up subdividing the bands by high angle grain boundaries and in turn grain refinement. The occurrence of recrystallization in shear bands has been also discussed by Kaibyshev et al. in aluminium alloys [23]. The occurrence of dynamic recrystallization refers to a process of negative work hardening, i.e. to situations where the dislocation density decreased with strain. Under this condition, the dislocation and low-angle boundaries densities become unstable with respect to the continued deformation. During each unit of further strain more dislocations are destroyed by recovery processes than are created by additional strain [12]. Thus the dislocation density in the subgrain interior is reduced. So, an extremely large strain may be actually achieved inside the shear bands.

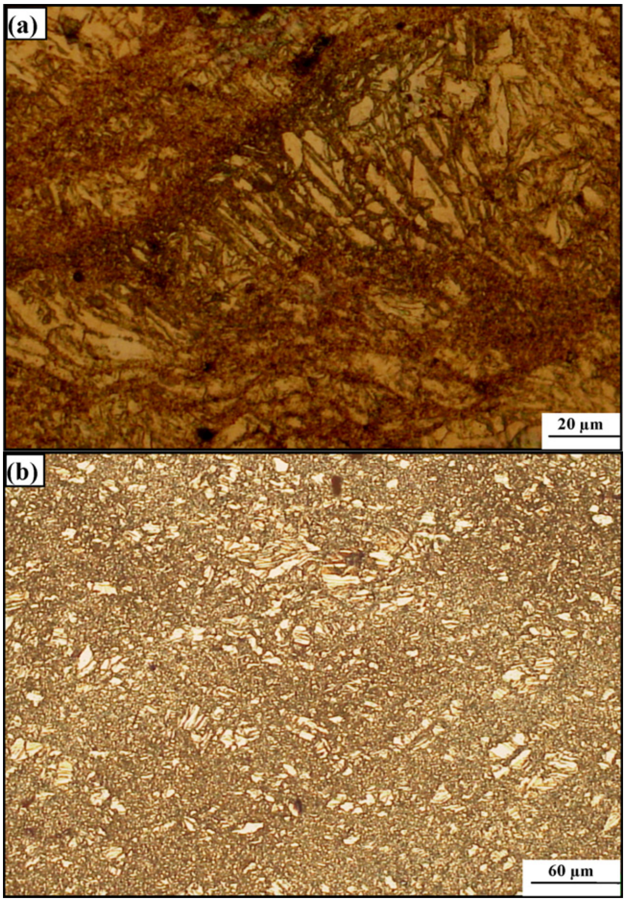

Fig. 7. (a) Propagation of shear band with the progress of second pass and (b) obtained microstructure after completion of ABE processing.

When material undergoes flow localization, the homogeneity within the samples can be easily evaluated by taking microhardness measurements. This was carried out at regions inside and outside the shear bands after step one and also at the end of one ABE cycle. The result is displayed in Fig. 6. Gradual strengthening may be observed from outside regions toward inside. It should be noted that the significant heterogeneity in mechanical properties may be rationalized by outstanding grain refinement in the bands. However, an acceptable homogenous mechanical property was measured across the cross section after completion of ABE cycle.

As the second step of ABE is applied, the shear bands propagate through deformed grains, as seen in Fig. 7a. This indicates that the strain tends to concentrate around the shear bands formed by the first step. The consequent propagation of shear bands may eventually yield a reasonably homogenous refined microstructure (see Fig. 7b).

Present results shows that shear banding phenomenon may be considered as a grain refining mechanism during SPD synthesis of AZ31 alloy, without harmful effect leading to premature fracture. This may be achieved where the deformation pattern associate with diffused shear bands well distributed all over the material. The latter was realized to be attainable in ABE process where adequate shear zones were anticipated during deformation [10].

4. Conclusions

- The appearance of shear banding was found during low temperature accumulative back extrusion of AZ31 magnesium alloy, the extent of which decreased by increasing temperature.
- Preferred twinning in favourite grains was believed to be the source of heterogeneous dynamic recrystallization.
- Dynamic recrystallization occurring in AZ31 alloy material was identified as a crucial factor that promotes strain localization.
- Outstanding grain refining was realized in the shear bands, which is believed to be the consequence of continuous dynamic recrystallization. The latter may give rise a large strain to be achieved inside the shear bands.
- Shear banding may be associated with significant heterogeneity in mechanical properties at regions inside and outside the bands.
- If it behaves well-distributed along the deformed material, shear banding phenomenon may be considered as a grain refining mechanism during severe deformation of AZ31 alloy.

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