Materials Science & Engineering A 618 (2014) 310–322

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Experimental and simulation analysis of texture formation and deformation mechanism of rolled AZ31B magnesium alloy under dynamic loading

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ARTICLE INFO

Article history:
Received 4 July 2014
Received in revised form
20 August 2014
Accepted 3 September 2014
Available online 18 September 2014

Keywords:
Rolled magnesium alloy
Mechanical anisotropy
Twinning
Deformation texture

ABSTRACT

Magnesium alloys components are potentially used under shock loading conditions. Considering the fact that deformation behavior is completely different under high strain rate conditions compared to quasi-static conditions, it is very important to evaluate the dynamic mechanical response and deformation mechanisms of magnesium alloys under impact loading. In this research, texture formation, micro-structural changes and dynamic deformation behavior of rolled AZ31B in the tempered H24 stress-relieved conditions, shock-loaded under compressive dynamic loading, were investigated. Texture measurements showed that the as-received AZ31B alloy had a strong (00.2) basal texture. Four groups of cylindrical samples were cut in the rolling direction (RD), in 45° to the RD, in the transverse direction (TD) and in the direction perpendicular to the RD–TD plane. Dynamic shock loading of the test samples were conducted using Split Hopkinson Pressure Bar at room temperature at strain rates ranging from 600 to 1100 s^{-1}, while loading direction was parallel to the longitudinal axis of the cylindrical samples. After high strain rate deformation, although the loading direction was different, a strong (00.2) basal texture was observed in all samples. It was inferred that increasing the strain rate led to an increase in strength and ductility, but to a decrease in twinning fraction, indicating the possible activation of non-basal $<c+a>$ slip systems. Besides, a high degree of mechanical anisotropy was found for all strain rates used such that the lowest strength was registered for the samples cut along the direction parallel to the rolling direction. A viscoplastic self-consistent model with a tangent approach was used to corroborate the experimental textures and possible deformation mechanisms by simulation.

1. Introduction

Magnesium alloys are increasingly used in the automotive and aerospace industries due to their low weight and high specific strength, which result in improved fuel efficiency and reduced greenhouse gas emissions [1–3]. In some structural applications, components are supposed to work under a wide range of strain rates. For example, the mechanical behavior at high strain rates is of great interest for automotive and aerospace industries because some critical components must be able to show appropriate resistance to failure under severe loading conditions such as car crash or bird-strike on airplane [4–6]. Unfortunately, structural applications of wrought magnesium sheets are very limited due to low room temperature elongation and strong plastic anisotropy, resulted from the strong (00.2) basal texture after forming processes such as rolling in which most of the grains are oriented such that their basal planes are parallel to the sheet plane. This strong basal texture may give rise to plastic anisotropy or low formability at loading directions, which are unfavorable for deformation [4–6].

Magnesium and its alloys generally deform by basal $<a>$ slip systems, which are the easy glide system in magnesium [2,4–6,7–10]. Basal slip systems, however, provide only two independent slip systems without accommodating any plastic strain along the *c*-axis. Activation of the pyramidal $<c+a>$ slip systems may provide more degree of freedom that is required for the arbitrary homogenous deformation as confirmed by some researchers [11–16]. Deformation twinning, including {10–12} extension (tension), {10–11} or {10–13} contraction (compression) and double twins, can also accommodate plastic strains along *c*-axis and provide more deformation mode for a homogenous deformation [4–6,17–22]. Considering the fact that basal slip only accommodates the strain along $<a>$ direction and

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http://dx.doi.org/10.1016/j.msea.2014.09.043
0921-5093/

pyramidal $<c+a>$ slip systems are activated at elevated temperature to allow a contribution to deformation in $<c>$ direction, it can be concluded that twinning plays an important role during the deformation of magnesium alloys at room temperature [17–22].

Since the deformation behavior of wrought magnesium alloys is highly dependent on the initial texture, it is very important to evaluate and understand the dynamic mechanical behavior and microstructural evolution of magnesium alloys under impact loading in different loading directions. However, the mechanical behavior and deformation mechanisms of magnesium alloys under shock loading conditions have not yet been comprehensively investigated. Particularly, the effect of initial texture on the microstructural evolution, deformation mechanisms and anisotropic mechanical properties is still not very clear. The studies that have been conducted to date have mostly focused on extruded AZ and AM alloys [23–28] and there are a few reports on the dynamic mechanical behavior and microstructural evolution of the AZ31 sheet, which are only based on experimental results [29–32]. For example, it was shown that the fracture morphology of AZ31B under high strain rates and high temperatures is mainly composed of the dimple pattern, indicating ductile fracture under these conditions [32]. In another research, it was observed using SEM that by increasing the strain rate, the twinning fraction decreased and it was ascribed to the possible localized flow [31]. However, as mentioned previously, the information on dynamic behavior of AZ31B in the open literature is very limited and there is no comprehensive report about texture measurement, microstructural evolution, mechanical properties, simulation of texture and their correlations in the open literature. Therefore, the main aim of the current study is to investigate the effects of initial texture and high strain rate deformation on the texture evolution, microstructural change, deformation mechanisms and anisotropic mechanical behavior of rolled AZ31B alloy by both experimental and simulation analysis. The samples were tested under different high strain rate conditions using Hopkinson bar apparatus and the correlation between the initial textures, deformation mechanisms and mechanical properties is discussed. Besides, a Visco-Plastic Self-Consistent (VPSC) model with a tangent approach was used to corroborate the experimental textures and deformation mechanisms by numerical simulation. The results can be an important addition to the current knowledge available on the deformation mechanisms of AZ31B magnesium alloys at high strain rate conditions.

2. Experimental procedure

2.1. Material and shock-loading test

Hot-rolled AZ31B magnesium alloy sheet in the tempered H24 stress-relieved conditions was used in this research. The nominal chemical composition of the alloy is Mg–3Al–1Zn. The compressive mechanical behavior of the samples at high strain rates was investigated using Split Hopkinson Pressure Bar (SHPB) at strain rates of 600, 800 and 1100 s^{-1}. In order to ensure different initial texture, four groups of samples (Fig. 1) used for shock loading experiments were cut in the rolling direction (RD, denoted as IP0), in 45° to the RD (denoted as IP45), in the transverse direction (TD, hereafter denoted as IP90) and in the direction perpendicular to the RD–TD plane (denoted as OP). The shock loading samples were machined from the as-rolled sheet into cylindrical shaped samples and all samples had the same height of 10.5 mm and diameter of 9.5 mm. Direction of compression was parallel to the longitudinal axis of all cylindrical samples (Fig. 1). A blunt projectile (striker), which was fired by a gas gun, traveled through the gun barrel, striking the test sample at high impact momentum. On impacting

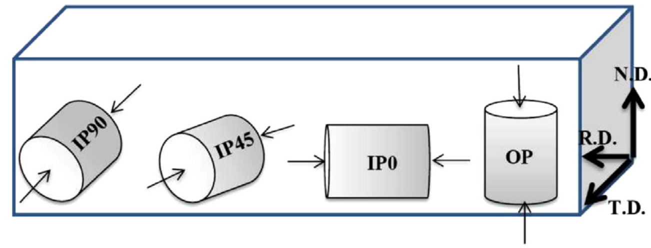

Fig. 1. Schematic diagram of the samples for shock loading tests and corresponding compression directions (thin arrows).

the samples, an incident strain pulse was produced that traveled along the input (incident) bar and after reaching the sample, it was partially reflected back as the reflected strain (ε_R) and partially transmitted to the output (transmitter) bar as transmitted (ε_T) strain. The input bar, output bar and striker are made of maraging steel 300 (Mar 300). Using strain gauges on the input bar, measurement of the incident and reflected strains were done and the transmitted strains were measured by a strain gauge on the output bar. Related equations were used to calculate the sample strain, stress and strain rate. For example, the strain rate is given by Eq. (1) [33,34]:

$$\dot{\varepsilon} = (-2C_0/l_s)\varepsilon_R \quad (1)$$

where C_0 is the sound velocity in the bars and l_s is the initial length of the sample. The detailed information about the Split Hopkinson Pressure bar formulae and equations can be found in the literature [33,34]. Vaseline was used to lubricate the sample ends to eliminate the friction effect during impact. To check the repeatability and consistency of the results, three tests were conducted and the averages of the results were registered and reported. The variation in stress was very low and was generally less than 5%.

2.2. Texture measurements

The texture of the samples, before and after shock loading, was measured using X-ray diffraction (XRD). The compression plane, i.e. the plane which was perpendicular to the compression direction, was considered for texture measurements in all samples (e.g. 'RD–TD' plane for OP sample, 'TD–ND' plane for IP0, 'RD–ND' plane for IP90 and 'ND–DRD' plane for IP45). The X-ray diffraction (XRD) experiments were done by a Bruker D8 discover diffractometer, equipped with a texture goniometer using Cu Kα radiation and VANTEC 500 area detector. Furthermore, six incomplete pole figures (PF), namely (10.0), (00.2), (10.1), (10.2), (11.0) and (10.3) were calculated and (00.2) and (10.0) pole figures were presented. Using incomplete pole figures, orientation distribution function (ODF) was determined by ResMat software. Finally, inverse pole figures (IPF) were plotted.

2.3. Microstructural characterization

For characterization of the samples' microstructure, a field emission scanning electron microscope Hitachi SU6600 FE-SEM was used. Orientation Imaging Microscopy (OIM) was used to study grain orientation and twins type via electron backscattered diffraction (EBSD) with the aid of a Hitachi SU6600 FE-SEM fitted with Oxford Instruments. Data analysis was carried out using (hkl) Channel 5 data acquisition and analysis software.

To prepare the samples for orientation imaging microscopy (OIM), they were polished with 2000 and 4000 SiC papers followed by 3, 1 and 0.25 μm alcohol-based diamond suspensions. The final step of polishing was done using colloidal silica solution (0.04 μm) mixed with ethanol and ethylene glycol. To minimize