Journal of Alloys and Compounds 656 (2016) 539–550

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Understanding low-cycle fatigue life improvement mechanisms in a pre-twinned magnesium alloy

Wei Wu, Ke An*

Chemical and Engineering Materials Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

ARTICLE INFO

Article history:
Received 17 August 2015
Received in revised form
22 September 2015
Accepted 28 September 2015
Available online 3 October 2015

Keywords:
Magnesium alloy
Mechanical properties
Anisotropy
Neutron diffraction

ABSTRACT

The mechanisms of fatigue life improvement by pre-twinning process in a commercial rolled magnesium (Mg) alloy have been investigated using real-time in situ neutron diffraction under a continuous-loading condition. It is found that by introducing the excess twinned grains through pre-compression along the rolling direction the fatigue life was enhanced approximately 50%, mainly resulting from the prolonged detwinning process and inhibited dislocation slip during reverse tension. Moreover, after pre-twinning, the reduction of the rapid strain hardening during reverse tension leads to a compressive mean stress value and more symmetric shape of stress–strain hysteresis loop. The pre-twinning has significant impacts on the twinning-detwinning characteristics and deformation modes during cyclic loading and greatly facilitates the twinning-detwinning activities in plastic deformation. The cyclic straining leads to the increase of contribution of tensile twinning deformation in overall plastic deformation in both the as-received and pre-twinned sample. The mechanisms of load partitioning in different groups of grains are closely related to the deformation modes in each deformation stage, while the fatigue cycling has little influence on the load sharing. The pre-twinning process provides an easy and cost-effective route to improve the low-cycle fatigue life through manufacturing and processing, which would advance the wide application of light-weight wrought Mg alloys as structural materials.

1. Introduction

The development of lightweight, high strength, and cost-effective materials is essential for the energy-efficient vehicles, which will reduce the weight of automobile, consumption of fossil fuel, and green-house gas emission, without compromising the performance and reliability [1–3]. The wrought magnesium (Mg) alloy is a perfect candidate to meet those criteria. As load bearing components, the materials suffer from cyclic loading, which could result in the catastrophic failure during the service. Therefore, the improvement of fatigue properties in currently commercially available Mg alloys is certainly worth the effort of researchers to promote the wide application of Mg alloys as structural materials [4–6]. There are many ways to enhance mechanical properties in Mg alloys, including the rare earth element addition [7–10], optimizing the microstructures [11–18], and controlling the initial texture [19–21], and so on. It can be achieved by metallurgy, heat-treatment, manufacturing and processing (rolling, extrusion, drawing, bending, and stretching), etc.. In previous studies [22–27], it has been reported that the alternate {10.2} twinning and detwinning processes are often involved in highly textured wrought Mg alloys during cyclic straining, which can be influenced by chemical composition, microstructure, and initial texture et al.. Among them, manipulating the initial texture through pre-twinning can be easily and cost-effectively accomplished by manufacturing and processing, which will efficaciously modify the low-cycle fatigue properties of wrought Mg alloys.

The hexagonal close-packed (HCP) structured Mg has two easy deformation modes, namely, basal <a> slip {00.2}<11.0>and tensile twinning {10.2}<10.1> [28,29]. The {10.2} tensile twinning can be activated by tension parallel to the c-axis or compression perpendicular to the c-axis, which leads to a sudden reorientation of lattice approximately 86.3° [22,23]. The detwinning process can be initiated during the stress- or strain-reversal in the re-orientated lattice in the twinned region. The comprehensive studies [20,22–24,26,30–43] have been conducted in the past two decades to characterize the twinning and/or detwinning process in HCP-structured crystalline materials during plastic deformation, strain-path changes, and cyclic loading.

* Corresponding author. Chemical and Engineering Materials Division, Oak Ridge National Laboratory, 1 Bethel Valley Rd, Oak Ridge, TN 37831, USA.
E-mail address: kean@ornl.gov (K. An).

http://dx.doi.org/10.1016/j.jallcom.2015.09.247
0925-8388/

The asymmetric shape of the stress-strain hysteresis loop is usually observed in wrought Mg alloys during fully reversed low-cycle fatigue when the total strain amplitude is larger than +/− 0.005 [39]. In our previous study [26], the low-cycle fatigue behavior of a rolled AZ31 Mg alloy has been investigated using real-time in situ neutron diffraction under continuously loading condition at total strain amplitude +/− 0.02, at room temperature. It was found that the asymmetry of the stress–strain hysteresis loop was attributed to the early exhaustion of the detwinning process, due to the insufficient twinned grains. It is expected that pre-twinning will provide a large amount of twinned grains that would change the twinning and detwinning characteristics during cyclic loading, and therefore affect the low-cycle fatigue life. Hitherto, the research regarding the effect of pre-twinning on low-cycle fatigue behavior of wrought Mg alloys is sparse. It has been demonstrated that pre-twinning by pre-tension in "ND" sample (loading direction parallel to ND of the rolling plate) derogated the low-cycle fatigue life, because of the development of the tensile mean stress and ductility loss caused by the pre-tension [44]. On the contrary, the pre-twinning by pre-compression in "RD" sample (loading direction parallel to RD) enhanced the fatigue life by reducing the mean stress [45,46]. Thus, the pre-twinning process could have either positive or negative impact on the low-cycle fatigue properties, which highly depends on the initial texture, loading path, and sample orientation.

Stemming from the lack of direct in situ observation, the effect of pre-twinning on the deformation mechanisms during low-cycle fatigue remains unclear, such as 1) what is the reason for fatigue life improvement after pre-twinning from a microscopic point of view, 2) how the twinning and detwinning activities vary after the pre-twinning, and 3) what controls the load partitioning in different groups of grains during deformation? The current paper concentrates on investigation of the above-mentioned three subjects by using real-time in situ neutron diffraction method under a continuous-loading condition to provide the first-hand evidence during cyclic straining.

2. Material and methods

2.1. Experimental materials

A commercial AZ31B Mg alloy after rolling (a nominal composition of 3.0% Al, 1.0% Zn, and Mg as balance, in weight percentage) with typical rolling texture was selected in the current study. The initial texture of the rolling plate was published elsewhere [24]. The low-cycle fatigue samples were machined according to the American Society for Testing and Materials (ASTM) Standard E606-04 in a cylindrical dog-bone shape, with 8 mm diameter and 16 mm gage length. The axial direction of fatigue specimens was parallel to the rolling direction (RD) of the rolling plate. An arrow was marked on the end of each specimen to indicate the normal direction (ND) of the rolling plate in the radial direction. Before the mechanical loading, all specimens were annealed at 345 °C for 2 h to release the residual stress generated from the manufacturing and sample machining. The microstructures of annealed AZ31B rolled Mg alloy in transverse direction (TD)-ND and TD-RD planes are demonstrated in Fig. S1(a) and (b), respectively. The average grain size of annealed sample was approximately 40 μm.

2.2. Mechanical testing

The fully reversed low-cycle fatigue experiments were conducted at a total strain of +/− 0.02, at room temperature with triangular loading waveforms and 1 Hz frequency. It is worth mentioning that the fatigue tests were started from compression, unlike the conventional low-cycle fatigue tests starting from tension, in order to initiate the twinning dominated deformation at the beginning. The constant strain rate, $3.33 \times 10^{-5}\ s^{-1}$ was applied during neutron diffraction measurements on one sample, designed as "As-received sample". The 1st, 2nd, 5th, 10th, 20th, 50th, and 80th cycles were chosen for the real-time in situ neutron diffraction measurements. Another sample was pre-compressed to − 0.04 strain under a constant strain rate, $2.22 \times 10^{-5}\ s^{-1}$, and then unloaded to 0 N. Then the same experiment scheme as the as-received sample was applied, except the strain rate was changed to $1.11 \times 10^{-5}\ s^{-1}$ and the neutron diffraction measurements were performed in 1st, 2nd, 5th, 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90th, 100th, 110th, 120th, and 130th cycles.

2.3. Neutron diffraction measurements

The real-time in-situ neutron diffraction measurements were conducted using the recently-developed state-of-the-art VULCAN Engineering Diffractometer at the Spallation Neutron Source (SNS) of the Oak Ridge National Laboratory (ORNL) under a continuous loading condition [47–49]. The detailed experiment setup has been described in detail elsewhere [25,26,38,50,51]. Only a brief description is provided here. The VULCAN MTS loadframe was laid horizontally. The specimen was aligned with loading direction parallel to RD and the horizontal-radial direction along ND. The incident beam was 45° to the sample. The two detector banks were located at ± 90° to the incoming neutron beam. One detector bank recorded the diffraction patterns in axial direction, and the other received diffraction patterns in horizontal-radial direction, during the mechanical loading. The neutron beam slits was defined as 5 mm × 5 mm, with 5 mm receiving collimators. The high intensity mode and a 20 Hz chopper speed were chosen for the as-received sample, while 30 Hz chopper speed was selected for the pre-twinned sample.

The event-based data reduction software, VULCAN Data Reduction and Interactive Visualization softwarE (VDRIVE) was used for data reduction after neutron diffraction measurements [52]. In the present paper, the binning time of 120 and 90 s were selected for as-received and pre-twinned sample, respectively, which are the shortest time bins without compromising the data quality for single peak fitting. In the meantime, the averaged loadframe information over the binning time, such as displacement, force, stress, and strain, were synchronized with the "chopped" diffraction patterns. To eliminate the neutron beam fluctuation during the measurement, the diffraction patterns were normalized to the incoming beam energy. Moreover, the instrument background was subtracted from the diffraction patterns for the normalization of diffraction peak intensity. The lattice strain of certain *hkl*, ε^{hkl}, was calculated using the well-known equation as follows,

$$\varepsilon^{hkl} = \frac{d^{hkl} - d_0^{hkl}}{d_0^{hkl}} \tag{1}$$

where d_0^{hkl} is the reference d-spacing before deformation and d^{hkl} is the d-spacing after deformation. The reference d-spacing, d_0^{hkl}, was measured for 500 and 1500 s, which are much longer than the binning time, for the as-received and pre-twinned sample, respectively, to diminish the propagated d_0^{hkl} statistical error. Since the rolled Mg samples are highly textured, some of *hkl*s cannot be detected or have very low peak intensities for the reference measurements, leading to a bad fitting of d_0^{hkl} from the single peak fitting. After deformation, the missing peaks will experience the appearing-disappearing sequence due to the twinning-detwinning