Journal of Alloys and Compounds 683 (2016) 619–633

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

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

Investigation of deformation twinning under complex stress states in a rolled magnesium alloy

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ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form
14 May 2016
Accepted 14 May 2016
Available online 15 May 2016

Keywords:
Metals and alloys
Mechanical properties
X-ray diffraction
Microstructure

ABSTRACT

A specially designed semi-circular notch specimen was employed in the current study to generate the various strain conditions, including uniaxial, biaxial, shear, and plane strains, which was utilized to explore the evolution of different deformation twinning systems under complex loading conditions. Using in situ synchrotron X-ray diffraction mapping method, it was found that the extensive double twins were activated during loading, while nearly no extension twinning activity was detected. After the formation of {10.1} and {10.3} compression twins, they transformed into {10.1}–{10.2} and {10.3}–{10.2} double twins instantaneously at the early stage of deformation. The lattice strain evolutions in different *hkl*s were mapped at selected load levels during the loading-unloading sequence. The relationship between the macroscopic straining and microscopic response was established.

1. Introduction

Magnesium (Mg) alloys are the lightest among commercial metals for the structural applications, which has drawn great attentions from academic society and transportation industries due to the combined properties of high strength-to-weight ratio and high specific stiffness [1,2]. Compared with casting Mg alloys, wrought Mg alloys exhibit superior mechanical properties and fatigue resistance owing to their defect-free nature [3]. The mechanical properties of wrought Mg alloys can be further improved through heat-treatment, grain refinement, and rare earth element addition [4–10]. Therefore, the study of deformation behavior of wrought Mg alloys is inevitable for promoting the wide applications of Mg alloys as load-bearing components.

Mg has a hexagonal close-packed (HCP) crystal structure with a limited number of slip systems leading to an anisotropic plastic deformation behavior [11,12]. It has been established that {00.2} ⟨11.0⟩ basal <a> slip and {10.2} ⟨10.1⟩ extension twinning are the two easy deformation modes in the HCP-structured Mg [13,14]. The {10.2} ⟨10.1⟩ extension twinning can be activated by tension along c-axis and compression perpendicular to the c-axis, which results in a sudden re-orientation of parent grains by approximately 86.3° [15,16]. A plateau is usually perceived in stress-strain curve during the extension twinning dominated deformation, followed by a rapid strain hardening once the extension twinning dominated deformation exhausts, which leads to an early fracture. Comprehensive researches have been concentrated on the {10.2} ⟨10.1⟩ extension twinning in highly textured wrought Mg alloy during uniaxial tension, compression, and cyclic straining in the past two decades [17–25].

Besides the {10.2} ⟨10.1⟩ extension twinning, there are several twinning systems in the HCP-structured Mg, including the {10.1} and {10.3} contraction twinning and the {10.1}–{10.2} and {10.3}–{10.2} double twinning [26–29]. For the {10.1}–{10.2} double twinning system, there are four possible variants (type 1, type2, type3, and type4) of double twinning [26]. When the HCP-structured crystal experiences compressive stress along the c-axis or tensile stress perpendicular to the c-axis, it is a favorable stress state for the initiation of the {10.1} or {10.3} contraction twins. After the formation of the {10.1} or {10.3} contraction twins, the {10.2} secondary extension twins will be activated, because the stress state that favors the contraction twinning also facilitates the secondary extension twinning within the primary twin domain [30]. It has been reported that the compression twinning and double-twinning occurred after necking, indicating that large plastic

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http://dx.doi.org/10.1016/j.jallcom.2016.05.144
0925-8388/

deformation is required [31]. Compared with the research on extension twinning, studies focused on contraction twinning and double twinning are rare. Moreover, the evolution of compression twinning and double twinning in the bulk sample during in situ deformation remains unknown.

In reality, the structural components usually suffer from the complex loading condition during service other than simple tension or compression. In addition, during sheet metal forming, the materials are under complex multiaxial deformation process and many twinning/slip systems would be triggered. In the current study, a specially designed semi-circular notch sample was exploited to generate the strain/stress concentration around the notch to facilitate the activation of compression twinning and double-twinning deformation. Moreover, the complex biaxial stress states were produced around the notch, which was utilized for characterizing the correlation between the complex strain states and different deformation twinning systems. To the authors' best knowledge, the current study is the first attempt to characterize the compression twinning and double twinning deformation behavior in the HCP-structured Mg alloy during in situ synchrotron X-ray diffraction mapping under load. In the current paper, we address three critical issues, including, (1) how the different deformation twinning systems evolve under loading? (2) what are the lattice strain and stress distribution during deformation? (3) what is the favorite strain state for each twinning systems?

2. Material and methods

2.1. Experimental materials

A commercial AZ31B Mg rolling plate (a nominal composition of 3.0% Al, 1.0% Zn, and Mg as balance, in weight percentage) with typical rolling texture was chosen. The initial texture of the rolling plate was published elsewhere [18]. The sample geometry is illustrated in detail in Fig. 1(a). Two semi-circular edge notches with a diameter of 8 mm were cut on both sides of the plate dog-bone samples. The axial, transverse, and through thickness directions of specimens were aligned with the rolling direction (RD), normal direction (ND), and transverse direction (TD) of the rolling plate, respectively. The "center of notch" is marked in Fig. 1(a), which will be used throughout paper. After sample machining, all specimens were annealed at 345 °C for 2 h to release the residual stress. The average grain size of the annealed sample is approximately 40 μm.

2.2. Mapping experiments

Digital image correlation (DIC) method was employed to map the macroscopic strain evolution during tension. The uniaxial tension experiment was conducted using INSTRON ElectroPuls E–3000 testing system, with a fixed displacement rate of 0.008 mm/s. A digital camera was operated at 0.5 fps (frame per second) during the in situ measurement. The recorded digital images were analyzed using VIC 2D software to compute the surface strain maps for each captured image.

The synchrotron X-ray diffraction mapping experiment was performed at 11ID-C, Advanced Photon Source (APS), Argonne National Laboratory (ANL). The monochromatic beam with energy of 115 keV was used to conduct the experiment in forward scattering mode. The combination of the forward Bragg diffraction geometry and high energy x-ray makes the scattering vector nearly parallel to the surface of the specimen. The beam size of 0.2×0.2 mm^2 was used to map out the region of interest (notch area) with step size of 0.2 mm. The attenuation length of 115 keV synchrotron X-ray on AZ31 alloy is 3.55 cm (calculated using mass attenuation coefficient of 0.159 cm^2/g and density of 1.77 g/cm^3 for AZ31), which exceeds the thickness of the sample (2.5 mm) in the present study. Considering the beam size coupled with sample thickness of 2.5 mm and average grain size of 40 μm, approximately 1500–1600 grains were detected in each measurement. The mapping area is demonstrated in Fig. 1(a). The lattice strain mapping was conducted for the total of eight load levels, i.e., 0, 1000, 1500, 2000, 3000, 2000, 1000, and 0 N, in a single loading-unloading cycle. A cross was marked in the center of the sample as a reference location to ensure that the same area was measured at each load level.

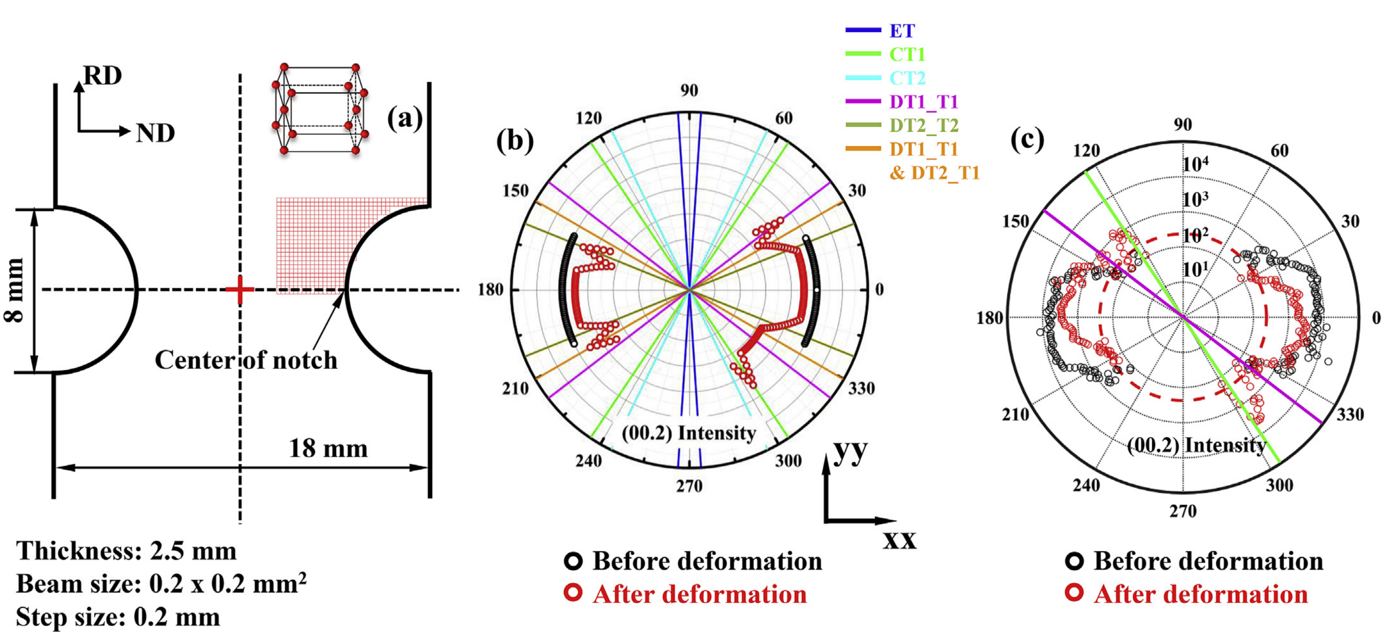

Fig. 1. (a) Sample geometry and mapping area of semi-circular notched plate dog bone specimen. (b) and (c) The simulation and experimental results, respectively, of (00.2) peak intensity distribution before and after deformation.