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Effect of strain ratio on cyclic deformation and fatigue of extruded AZ61A magnesium alloy

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ABSTRACT

Strain-controlled fatigue experiments were conducted on an extruded AZ61A magnesium alloy at three strain ratios ($R_\varepsilon = -\infty, -1, 0$) using smooth tubular specimens. As the strain ratio decreased, stronger cyclic hardening, more asymmetric hysteresis loop, smaller stress amplitude, lower mean stress, and higher initial plastic strain amplitude were observed. These phenomena were associated with twinning in the compressive phase and detwinning in the tensile phase during cyclic deformation. At the same strain amplitude, fatigue life increased with decreasing strain ratio. The strain-fatigue life curve at each strain ratio exhibited a distinguishable kink. Such a kink point represents a demarcation point above which persistent twinning–detwinning occurs under cyclic loading. Two Smith, Watson, and Topper (*SWT*) fatigue criteria can predict the fatigue lives of the material at all strain ratios satisfactorily.

1. Introduction

Due to low density, high specific strength and high specific stiffness, wrought magnesium (Mg) alloys are increasingly used as load-bearing components in automotive and aerospace industries for weight reduction and fuel economy improvement [1]. Fatigue behavior of Mg alloys is a major concern for the structural applications [2,3]. Due to a pronounced basal texture, wrought Mg alloys show a strong anisotropy in fatigue properties [4–6]. With a hexagonal close packed structure and a limited number of slip systems, both dislocation slip and mechanical twinning are the dominant deformation mechanisms. Under cyclic loading with a limited strain amplitude, $\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$ twinning is the most commonly and easily activated twin mode [7–10]. Since the c/a ratio of Mg is smaller than the ideal hard-sphere value of $\sqrt{3}$, the $\{10\bar{1}2\}$ twin is of a "tension" type: its activation is associated with the extension parallel to the c-axis of the crystal. Due to the pole nature of twinning in Mg alloys, the activation of mechanical twins is loading direction-dependent [10,11]. Under cyclic loading, detwinning occurs when the load which leads to the formation of mechanical twins is reversed [12–17]. The involvement of twinning–detwinning process and the interaction between dislocations and mechanical twins lead to anomalous mechanical behaviors of wrought Mg alloys, such as tension–compression asymmetry under monotonic loadings [12,18,19] and asymmetric sigmoidal-shaped stress–strain hysteresis loop under cyclic loadings [13–16].

Low-cycle fatigue behavior of Mg alloys under fully reversed strain (or stress) controlled tension–compression have been extensively studied in the last decade [4,6,20–36]. Recently, cyclic deformation and fatigue properties of Mg alloys under multiaxial cyclic loading were also explored by several investigators [37–40]. However, little work has been conducted with respect to the load ratio (minimum over maximum during a loading cycle) influence on cyclic deformation and fatigue behavior of Mg alloys [24,31,41]. Earlier findings on extruded AZ31 and AM30 Mg alloys under asymmetric cyclic loading revealed that, with a lower strain ratio, lower stress amplitude and mean stress, a higher plastic strain amplitude and a longer fatigue life will be observed [24,31].

Wrought AZ61A is one of the most common commercial Mg alloys and limited works have been studied on its fatigue properties [30,37,38,42–45]. Shih et al. [42] studied the fatigue mechanisms of an extruded AZ61A alloy in a rotating bending test. Fatigue cracking initiated from subsurface or surface inclusions, which served as stress raisers and induced clusters of slip bands during the rotating bending test. Deformation twins were induced from the blunting process at the crack tip and microscopic cracks occurred there. The propagation of fatigue cracks followed the initiation of microcracks and resulted in a transgranular cleavage fracture. Chamos et al. [43] observed that the *S*–*N* curve of a hot rolled AZ61 alloy exhibits a smooth transition from the low-cycle regime to the high-cycle regime. Fatigue crack initiation was transgranular while the propagation was intergranular. Li et al. [30]

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investigated the fatigue property of an extruded AZ61A alloy under fully reversed strain-controlled tension–compression. The strain–life fatigue curve displayed a detectable transition from the low-cycle regime to the high-cycle regime in the vicinity corresponding to a strain amplitude of 0.5%. When the strain amplitude was higher than 0.5%, shear cracking and abundant residual twins were observed. When the strain amplitude was lower than 0.5%, tensile cracking and marginal residual twins were observed. Recently, cyclic deformation and fatigue of an extruded AZ61A alloy under fully reversed strain-controlled tension–compression, cyclic torsion, and in-phase and out-of-phase axial-torsion were systematically investigated [37,38]. The asymmetry of hysteresis loops and the magnitude of mean stress depended on the loading path and the strain amplitude.

The objective of the current work is to evaluate the cyclic deformation and fatigue property of an extruded AZ61A Mg alloy under asymmetric cyclic loading with different strain ratios. No such work on this alloy has been reported in the literature. The cyclic stress response, change of mean stress, evolution of plastic deformation, fatigue life, and residual twin observation are presented. Based on the experimental results, two fatigue criteria are evaluated for their capability to predict fatigue life.

2. Material and experimental procedure

The material used in the current investigation is extruded AZ61A Mg alloy which is identical to the material used in the earlier study [37,38]. The material has a chemical composition in weight percentage of 6.5 Al, 0.95 Zn, 0.325 Mn, 0.1 Si, 0.05 Cu, 0.005 Fe, 0.005 Ni, and 0.3 other impurities, balanced by Mg. The thin-walled tubular specimen used in the current study has identical geometry and dimensions to that employed in the previous investigation [37,38]. It was machined from commercially acquired extruded tubing with an outer diameter of 25.91 mm, a thickness of 2.29 mm, and a gage length of 25.4 mm. The gage section of the testing specimen was finely ground before fatigue experiment. No heat treatment was made on the material before and after the specimen fabrication. Optical microscopy revealed that the extruded AZ61A Mg alloy consists of equiaxed grains with an average grain size of approximately 20 μm. There are precipitates at the grain boundaries, most probably the intermetallic compounds β-phase $Mg_{17}Al_{12}$ [42]. Twins were not observed in the undeformed state.

The initial macrotexture of the AZ61A Mg alloy was analyzed by X-ray diffraction. A cubic material sample was cut from the gage section of the tubular specimen (see Fig. 1). The sample coordinates fixed on the material sample has three orthotropic directions: extrusion direction (ED), tangential direction (TD), and radial direction (RD). Panalytical XPERT MPD PRO diffractometer was used to determine the initial texture on the plane which is normal to the RD direction. A GONIO scan was first performed to determine the precise 2θ positions of the $(10\bar{1}0)$, (0002), and $(10\bar{1}1)$ peaks. The intensity of (*hkil*) pole was collected on the diffraction plane which was designated by a plane normal *N*(*hkil*). The orientation of the diffraction plane normal is described by the azimuth angle (φ) and the polar angle (ψ) of a sphere coordinates fixed on the sample coordinates. Diffraction plane is changed by rotating the azimuth angle (φ) from 0° to 360° in a 5° incremental step and rotating the polar angle (ψ) from 0° to 85° in a 5° step. On each diffraction plane, the intensities of $(10\bar{1}0)$, (0002), and $(10\bar{1}1)$ diffraction peaks were collected at three corresponding 2θ positions, and used to construct the pole figures, respectively. Fig. 1 shows the $(10\bar{1}0)$, (0002), and $(10\bar{1}1)$ pole figures of the as-extruded AZ61A Mg alloy. Pole intensities are represented in terms of multiples of a random distribution (mrd). A typical basal texture of extruded Mg alloy tube is exhibited. The majority of

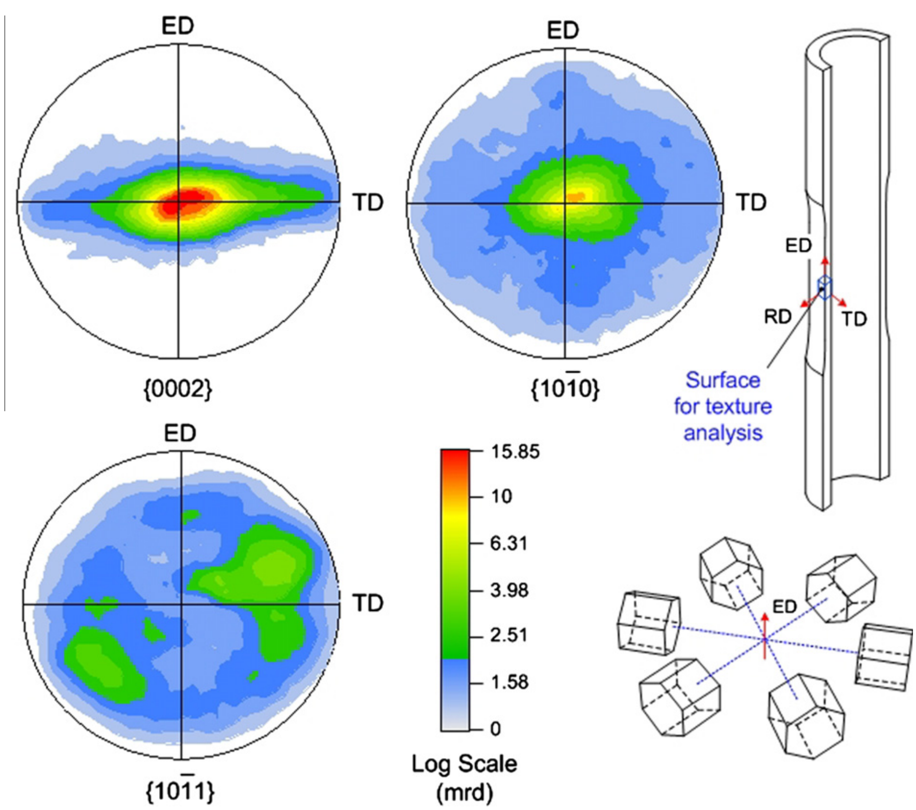

Fig. 1. Pole figures from X-ray diffraction showing the initial macrotexture of the extruded AZ61A Mg alloy (pole intensities are expressed in terms of multiples of a random distribution, mrd).