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An experimental study of the orientation effect on fatigue crack propagation in rolled AZ31B magnesium alloy

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ABSTRACT

Mode I fatigue crack growth (FCG) experiments were performed using compact tension (CT) specimens made of rolled AZ31B magnesium alloy in ambient laboratory air. The testing specimens were made with respect to two material orientations: a crack surface perpendicular to the rolled direction (R-T) and a crack perpendicular to the thickness or normal direction (N-T). The constant amplitude load experiments were performed at three load (R) ratios (minimum load over maximum load in a loading cycle) of 0.1, 0.5, and 0.75, respectively. Material orientation was found to affect the early crack growth stage more than the later stable growth stage. For each R-ratio, the threshold stress intensity factor range for the R-T specimens was less than that for the N-T specimens. Three sub-stages of steady crack growth were observed following the threshold stage: a low Paris law slope for the first sub-stage, a second sub-stage with a very high slope, and an intermediate slope during the third sub-stage. The R-T specimens exhibited an overall typical Mode I cracking direction, with occasional local deviation from the horizontal crack path. The N-T specimens displayed a general Mode I cracking with irregular crack pathing into the specimen away from the observation surface. Transgranular cracking was the primary cracking mode for both specimen orientations. Slip induced cleavage dominated cracking in both orientations. Few residual twins were found in the plastic zone area surrounding the crack tip, and no evidence of twin boundary cracking was found.

1. Introduction

Magnesium (Mg) alloys could significantly impact the future of structural materials due to their excellent physical properties such as exceptional specific strength and good machinability. In particular, the automotive industry is attempting to utilize these properties to help improve the fuel economy of vehicles [1]. Over the past two decades, studies were conducted to explore, understand, and improve the mechanical properties of Mg and its alloys.

Mg and its alloys have a hexagonal close-packed (HCP) crystal structure, which mechanically behaves differently from the more commonly used cubic structured materials due to fewer and more difficult to activate slip systems. Mg and its alloys deform primarily through a combination of two mechanisms: (0 0 0 1) basal slip and $\{1\ 0\ \bar{1}\ 2\}$ tensile twinning, the latter of which accommodates strain along the $<c>$ direction of the HCP crystal [2]. These two deformation mechanisms have a significant impact on crack initiation and propagation [3–8]. Additionally, the strong directionality of the deformation mechanisms results in a crack path that can deviate from the typical horizontal Mode I cracking direction seen in traditional cubic structures [8–13].

The deformation mechanisms and mechanical behavior in Mg alloys are dependent on the microstructure. Fatigue behavior is improved through grain refinement. In particular, reducing the grain size increases the stress required to activate twinning [14]. Barnett et al. [15] performed compression tests on extruded Mg-3Al-1Zn to examine the deformation mechanisms as a result of varying grain sizes and temperatures. It was found that there was a transition of deformation mechanism, from twinning to dislocation slip, as the grain size was reduced. Horstemeyer et al. [16] performed fully reversed fatigue tests on commercial high-pressure die cast automotive AZ91E-T4 Mg alloy. Their results showed that, for a given stress intensity factor range, the fatigue crack growth (FCG) rate was higher in a fine-grained microstructure than in a coarse-grained microstructure.

Metal processing can form a strong texture that affects the FCG behavior in wrought Mg alloys. Rolling or extrusion processes result in a majority of grains with their c-axes oriented in a particular direction relative to the working direction [9,17–23]. The texture formed due to the material processing leads to an anisotropic mechanical behavior. Twinning-detwinning during cyclic loading results in directional anisotropy and asymmetric stress-strain

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hysteresis loops under tension-compression loading [24-27]. Rolled Mg alloys typically contain a strong basal texture with the *c*-axes perpendicular to the rolled direction, along the "normal direction" [17,18]. Morita et al. [18] performed tension-compression tests on hot-rolled AZ31B Mg alloy. They reported that the FCG rate of a crack propagating perpendicular to the rolled direction was lower than that of a crack propagating parallel to the rolled direction at a similar stress intensity factor range. Wu et al. [28] also performed cyclic loading tests with a load ratio or *R*-ratio (minimum load over maximum load in a loading cycle) of 0.1 on rolled AZ31B compact tension (CT) specimens to examine the twinning-detwinning behavior surrounding and extending from the crack tip. They used specimens of the N-R orientation, where the loading direction is along the normal direction, which is parallel to the c-axes of many grains. It was found that reversible twinning-detwinning is the dominant deformation mechanism for the material studied, yet also revealed that only a small amount of residual twins remained following the loading. Morita et al. [29,30] performed FCG experiments on rolled AZ31B specimens at an *R*-ratio of 0.1 to examine the fracture surfaces. They found that crack propagation along the a-axis direction is favorable. They also reported very few residual twins along the crack path of the R-T orientation. Alternatively, extrusion results in a typical texture where the basal planes are primarily oriented parallel to the extrusion direction [9,21–23]. It was found that the crack growth resistance in the direction perpendicular to the extrusion direction is greater than that in the direction parallel to the extrusion direction. This effect is attributed to the basal texture and lamellar microstructure along the extrusion direction [9,19,20].

Loading parameters also affect the FCG behavior. An increase in *R*-ratio has been shown to increase the FCG rate in Mg alloys [9,29,31,32]. Zeng et al. [11,32,33] performed FCG experiments on single-edge notched plate specimens prepared from AZ61 and AZ80 Mg alloys. It was reported that, for a given stress intensity factor range, increasing the loading frequency resulted in a decrease of FCG rate within the studied alloy. Zheng et al. [34] examined the effects of overload and two-step loading on extruded AZ31B. A single tensile overload was found to greatly reduce the FCG rate a short length prior to returning to the expected FCG rate. The overload influencing zone was smaller in the extruded AZ31B than in other metallic materials [35–37]. Their results from the two-step loading experiments revealed that maintaining a constant maximum load in a loading cycle when reducing the *R*-ratio, mean load, or other loading parameter results in less retardation of the FCG rate.

While research on the FCG behavior of Mg and its alloys has increased in the past two decades, their behavior is not as well documented as other traditional metallic materials. In particular, the effect of specimen orientation and texture on FCG behavior has not been thoroughly examined. In the present study, the fatigue crack propagation behavior of rolled AZ31B Mg alloy is studied. The effects of specimen orientation in relation to the rolled direction and *R*-ratio on the FCG behavior are considered. Two specimen orientations and three different *R*-ratios are used.

2. Experiments

2.1. Material and microstructure

The material used in the current study is a commercially acquired rolled plate of AZ31B Mg alloy (Mg-3Al-1Zn). No heat treatment was applied after rolling. Fig. 1a is a three-dimensional isometric representation of the microstructure and initial texture of the rolled AZ31B Mg alloy obtained by electron backscatter diffraction (EBSD). The three planes have homogeneous microstructures consisting of mostly equiaxed grains with an average diameter/size of approximately 43 μm. Scattered residual twins as a result of rolling were found in the initial material, but not visualized in Fig. 1. Based on Fig. 1, this material shows a strong basal texture in which the c-axes of most grains align perpendicular to the R-T plane along the normal direction.

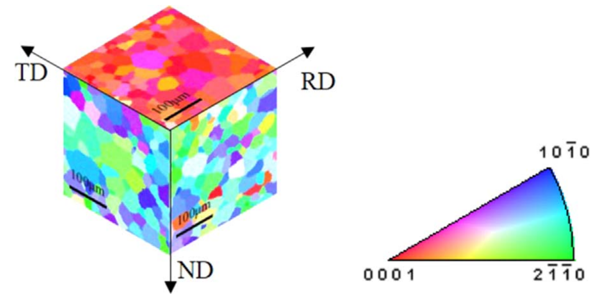

Fig. 1. Initial microstructure and macro texture of rolled AZ31B Mg alloy.

2.2. Specimen

Rectangular compact tension (CT) specimens were prepared for two orientations as shown in Fig. 2 where "RD," "ND," and "TD" denote the rolled/longitudinal, normal, and transverse directions, respectively. A designation of X-Y was used to identify the CT specimens. For Mode I crack growth, "X" designates the direction of the applied load and "Y" designates the cracking direction. For example, an R-T specimen is loaded in the rolled/longitudinal direction and the crack propagates along the transverse direction. For the other orientation, an N-T specimen is loaded in the normal direction and the crack grows in the transverse direction.

A sharp notch was made on the specimen using electrical discharge machining (EDM). Prior to testing, one specimen surface of each specimen was polished to a mirror-like finish by standard metallographic preparation techniques to facilitate crack observation and measurement. The specimen surfaces were sequentially ground using 360/P500 to 1000/P3200 silicon carbide grit papers. Polishing was done using 6 μm, followed by 1 μm oil based polycrystalline diamond suspensions. A final polish was achieved using 0.05 μm MasterPolish® suspension. The specimens were then etched in an Acetic-Picral solution (10 mL acetic acid, 4.2 g picric acid, 10 mL distilled water, and 70 mL ethanol) until surface browns, which usually occurred after approximately five seconds, to reveal the initial microstructure. Companion EBSD specimens were prepared in a similar manner, but were etched in 3% nital for 10 s to remove the final surface layer of damage.

2.3. Experiments

A servo-hydraulic load frame with a ±25 kN load capacity was used for testing the CT specimens. In order to accommodate the small load used in the experiments, a 2.0 kN load cell was used for the control of the load. All the experiments were conducted with constant amplitude load employing a sinusoidal waveform. The loading frequency was varied as a function of stress intensity factor range (ΔK), where the loading frequency was gradually decreased with increasing ΔK. A frequency of 20 Hz was used near threshold and the frequency was decreased to 2 Hz near the fast fracture region. Three load or *R*-ratios (minimum load over maximum load in a loading cycle) were used for the two specimen orientations. These values were 0.1, 0.5, and 0.75. The threshold stress intensity factor range, ΔK_{th}, was determined by sequentially reducing the load amplitude for a given *R*-ratio until the FCG rate was less than 1.0×10^{-7} mm/cycle. When the *R*-ratio was 0.5 and 0.75, the crack was initiated with an *R*-ratio of 0.1, and sequentially