Low Cycle Fatigue Properties and an Energy-Based Approach for as-Extruded AZ31 Magnesium Alloy

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(received date: 9 June 2010 / accepted date: 14 September 2010)

Low cycle fatigue tests were conducted to investigate the cyclic deformation behavior and the energy-based criterion of AZ31 magnesium alloy. The alloy exhibited an asymmetric hysteresis loop due to the twinning and detwinning effect. The cyclic stress responses showed cyclic hardening at all total strain amplitudes. To evaluate the plastic strain energy, the Halford-Morrow equation and a modified equation for magnesium alloy were compared. The effect of twinning on the total plastic strain energy dissipated during fatigue life was discussed. The variations of the twin and dislocation densities were also investigated using optical microscopy and transmission electron microscopy, respectively.

Keywords: alloys, extrusion, fatigue, microstructure, twinning

1. INTRODUCTION

As the demand for reducing CO₂ emissions and increasing the fuel efficiency grows, magnesium alloys have received an increasing amount of attention as structural materials due to their excellent properties, such as their high specific strength, low density and stiffness [1-3]. Since the c/a ratio of the hexagonal close-packed (hcp) magnesium lattice is less than √3, extruded magnesium alloys, which have a strong basal texture, show large yield asymmetries between tension and compression due to the twinning effects during compression along the prior extruded direction [4-9]. This anisotropy of magnesium alloys affects their fatigue properties to a considerable extent. Structural materials are frequently exposed to cyclic loading and plastic strain; therefore, the low cycle fatigue behavior of magnesium alloys has to be carefully studied for engineering design purposes. Although many studies have been conducted on the fatigue properties of magnesium alloys, very few of them focused on the energy-based fatigue criteria [9-14]. Energy-based approaches have been employed to evaluate the fatigue damage and to predict the fatigue lifetime [15,16]. During cyclic loading, energy is dissipated due to plastic deformation. The dissipated strain energy per cycle may be regarded as the main contributor to the fatigue damage process taking place during each cycle.

Finding the correlation between the strain energy and the fatigue life is desirable, as it allows the inclusion of both stress and strain for comprehensive studies of the fatigue properties [17]. Thus, these energy-based criteria may serve as a reasonable alternative to the stress- or strain-based ones [18]. The plastic strain energy dissipated within a cycle is the area of the hysteresis loop of low cycle fatigue. The total plastic strain energy is the sum of the plastic strain energy in each cycle during the total fatigue lifetime [15]. Conventional energy-based approaches to the evaluation of fatigue properties have focused on materials showing a symmetric hysteresis loop. However, this study proposes a new method to calculate the plastic strain energy of a magnesium alloy showing an asymmetric hysteresis loop. The objective of this investigation is to evaluate the low cycle fatigue properties and to study the energy-based approach of as-extruded AZ31 magnesium alloy.

2. EXPERIMENTAL PROCEDURE

The material used in this study was as-extruded AZ31 magnesium alloy. The chemical composition of the alloy is shown in Table 1. The alloy ingot was extruded at 260 °C followed by air cooling. Tensile tests were conducted using an Instron servo-hydraulic testing machine at a strain rate of 1 × 10⁻³ s⁻¹. The hardness test was carried out with a Shimadzu Vickers hardness tester. The obtained mechanical properties are shown in Table 2. Low cycle fatigue tests were
performed under total strain control in a computerized Instron testing system. A triangular waveform initiated from compression with total strain amplitudes ranging from 0.4 % to 1.2 % was applied at room temperature under a constant strain rate of $1 \times 10^{-2}$ s$^{-1}$. To observe the microstructural changes of the alloy, the gauge of the fatigue specimen was ground with SiC papers and polished with alumina powder solution. After polishing, the gauge area of the specimen was etched with an acetic-picral acid solution (4.2 g picric acid, 10 mL acetic acid, 10 mL H$_2$O, 70 mL and ethanol). The same region of the specimen was observed before the low cycle fatigue test, after the first compression, after the first tension, and after 150 cycles of fatigue. A microstructural analysis was performed using a JEM-2000EX TEM at 200 kV to investigate the effects of the dislocation density on the fatigue properties.

3. RESULTS AND DISCUSSION

3.1. Hysteresis loop and microstructure evolution

Figure 1 illustrates the stress-strain hysteresis loop of the AZ31 magnesium alloy at the first cycle under a total strain amplitude of 1.2 % starting from either compression or tension. However, the different shapes become identical after the second cycle. For the extruded magnesium alloys, the hysteresis loops of the low cycle fatigue test loaded along the extruded direction were asymmetric due to twinning and detwinning effects [4,7]. When the fatigue test was started from compression, the specimen yielded at point B and then was strained to point C with a minimal change in the stress caused by the twinning effect. Upon unloading from point C, the hysteresis loop exhibited a sigmoidal shape. At point D, the loop showed an inflection, which correlates with the exhaustion of the detwinning mechanism. When the detwinning process was complete, the resulting orientation resisted tensile deformation by basal slip [4]. This caused the cyclic tensile stress to be higher than the cyclic compressive stress.

Figure 2 shows the microstructural change of the AZ31 magnesium alloy. Figure 2(a) shows the microstructural image before the test, corresponding to A in Fig. 1(a). Figure 2(b) shows the alloy in the unloaded state after first compression (C in Fig. 1(a)). A comparison of these images showed that many twins were formed after the first compression. The state in Fig. 2(c) is when the load was removed after the first loading reverse from compression to tension at a total strain amplitude of 1.2 %. As shown in Fig. 2(d), an increase in the stress due to the cyclic deformation resulted in the disappearance or narrowing of the twins formed during the first compression.

Fig. 1. Hysteresis loop of the first cycle of fatigue under a total strain amplitude of 1.2 %: (a) starting from compression and (b) starting from tension.

Fig. 2. Microstructure evolution of the specimen: (a) initial state, (b) unloading state after first compression, (c) unloading state after first tension, and (d) after 150 cycles of fatigue at a total strain amplitude of 1.2 %.