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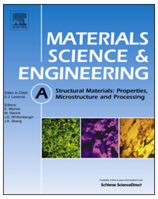

Uniaxial ratchetting of extruded AZ31 magnesium alloy: Effect of mean stress

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ABSTRACT

The uniaxial ratchetting of extruded AZ31 magnesium alloy was investigated in the cyclic tests with different mean stresses and at room temperature. The prescribed mean stresses and corresponding stress amplitudes were chosen to make the different plastic deformation mechanisms such as dislocation slipping, twinning and detwinning occur individually or simultaneously during the cyclic deformation of the AZ31 magnesium alloy with a hexagonal close packed crystal structure, and then the effect of mean stress on the uniaxial ratchetting of the magnesium alloy was discussed. It is seen that ratchetting occurs in the AZ31 magnesium alloy during the stress-controlled cyclic loading, but different evolution features are observed in the uniaxial ratchetting tests with different mean stresses. Different ratchetting behaviors are determined by the different deformation mechanisms of extruded AZ31 magnesium alloy occurring in the tensile and compressive parts of cyclic loading. A sigmoidal stress–strain hysteresis loop of the magnesium alloy presented in the cyclic tension–compression tests with some suitable mean stresses and stress amplitudes is caused by the twinning/detwinning deformation mechanism, which should be reasonably considered in constructing a cyclic constitutive model to describe the uniaxial ratchetting of magnesium alloys.

1. Introduction

Magnesium alloys have been widely used in automotive and aerospace industries due to their high specific strength and stiffness [1], and these structure components are often subjected to a cyclic loading. Then, the cyclic deformation of magnesium alloys is a key issue which should be investigated before the fatigue life and reliability of such components can be assessed. Therefore, in recent years, many experimental observations have been performed to investigate the cyclic deformation of magnesium alloys [2–10]. The existing observations demonstrated some specific cyclic stress–strain responses of magnesium alloy caused by its hexagonal close packed (HCP) crystal structure. The cyclic stress–strain responses of the extruded and hot-rolled magnesium alloys were strongly anisotropic in the tensile and compressive tests due to their basal plane textures formed in the manufacture, and their initial compressive yielding stresses were smaller than the tensile ones. Due to the low symmetry of hexagonal close packed crystal structure, the slip systems of magnesium alloy are limited. Although four modes of slip systems had been observed by Graff et al. [11], i.e., basal ⟨a⟩, prismatic ⟨a⟩, pyramidal ⟨a⟩ and pyramidal ⟨c+a⟩ slip systems, the dislocation slipping cannot be easily activated in non-basal slip systems due to their very high critical resolved shear stresses. Only the dislocation slipping in the basal ⟨a⟩ slip system can be activated in the process of loading. Thus, the deformation twinning plays an important role in the plastic deformation of magnesium alloys, as commented by Gharghouri et al. [12] and Caceres and Lukac [13]. Staroselsky and Anand [14] and Oppedal et al. [15] reported that two twinning systems, i.e., the extension twinning system $\{10\bar{1}2\}\langle10\bar{1}1\rangle$ and contraction one $\{10\bar{1}1\}\langle10\bar{1}2\rangle$, were popular in the magnesium alloys. However, the contraction twinning system cannot be easily activated if the strain is not high enough, e.g., smaller than 8% in uniaxial tension or compression [16], because its critical resolved shear stress was much higher than that of the extension one. From the detailed microscopic observations to the microstructures and their evolutions, Huppmann et al. [16] concluded that the extension twinning made a main contribution to the plastic deformation of extruded and hot-rolled magnesium alloys during the cyclic loading, especially in the beginning of cyclic loading. However, these existing researches were mainly discussed under the strain-controlled loading condition, and did not consider the cyclic

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stress–strain responses of magnesium alloys under the stress-controlled loading condition, which was also one of the important loading modes that the engineering structures often endure.

As reviewed by Ohno [17,18], Kang [19] and Chaboche [20], ratchetting, a cyclic accumulation of plastic deformation, will occur in the asymmetrical stress-controlled cyclic tests of engineering materials, if the applied stress is high enough to make the materials plastic yielding. Similar to the engineering materials reviewed in [17–20], recent research [21–28] demonstrated that ratchetting also occurred in the cyclic tests of some extruded or hot-rolled magnesium alloys under the stress-controlled cyclic loading conditions. Lin et al. [21,22] observed that the uniaxial ratchetting of hot-rolled AZ91D magnesium polycrystalline alloys depends greatly upon the applied mean stress, stress amplitude and stress rate. Zhang et al. [23–25] discussed the effects of extrusion ratio, annealing treatment and loading orientation on the ratchetting of extruded AZ31B magnesium alloy. Lin et al. [26] investigated the effect of stress ratio on the uniaxial ratchetting and fatigue failure of hot-rolled AZ91 magnesium alloy. However, as commented by Xiong et al. [27], the previous observations to the ratchetting of magnesium alloys were performed under the condition that no bulk deformation twinning occurred, and then the observed ratchetting of magnesium alloy was similar to those observed in the engineering materials with the face-centered cubic and body-centered cubic crystal structures, such as 304 and 316L stainless steels [28,29] and ordinary carbon steels [30]. The effects of bulk twinning and detwinning on the ratchetting of magnesium alloy were not investigated yet. More recently, Xiong et al. [27] performed experimental observations to the effects of twinning and detwinning on the ratchetting of extruded ZK60 magnesium alloy with a HCP crystal structure, and demonstrated three types of cyclic deformation features with regard to the twinning and detwinning processes. How about the other kinds of magnesium alloys, such as the extruded AZ31 magnesium alloy? Can any new cyclic deformation features be observed in the cyclic tests of the extruded AZ31 magnesium alloy?

Therefore, in this work, the uniaxial ratchetting of the extruded AZ31 magnesium alloy is investigated in the stress-controlled cyclic tests with different mean stresses and at room temperature. The prescribed mean stresses and corresponding stress amplitudes are chosen to make the different plastic deformation mechanisms such as dislocation slipping, twinning and detwinning (which have been reported by the existing references from the microscopic observations, such as in [6,31,32]) occur individually or simultaneously during cyclic loading, and then the effect of mean stress on the uniaxial ratchetting of the extruded AZ31 magnesium alloy is discussed. Some significant conclusions useful to construct a cyclic constitutive model to describe the ratchetting of magnesium alloy are obtained.

2. Experimental procedure

The experimental material is an extruded AZ31 magnesium alloy, and its chemical composition is Al, 3.05%; Zn, 0.82%; Mn, 0.40%; and Mg, balance (in mass). The extrusion conditions are given as follows: the extrusion ratio is 29.2; the temperature is 657 K; and the extrusion velocity is 4.94 m/min. A (0002) basal plane texture was obtained in the extruded AZ31 magnesium alloy bars. The extruded bars were first heated at 553 K for 30 min to release the residual stress, and then cooled in air, before they were machined to be the uniaxial solid-bar specimens with a gauge length of 8 mm and cross-section diameter of 6 mm. The tests were performed in MTS809 tension–torsion machine, and a triangle loading waveform was used. The strain was measured by a uniaxial extensometer. The specimens were mainly tested under the stress-controlled cyclic tension–compression conditions. It means that the loading directions of all the tests are parallel to the extrusion directions of the alloy bars. During the uniaxial cyclic tests, different mean stresses varied from positive to negative ones and corresponding stress amplitudes were prescribed to discuss different evolution features of the ratchetting of the AZ31 magnesium alloy. However, to realize the basic mechanical properties of the magnesium alloy, such as the yielding stress, strain hardening and cyclic softening/hardening features, the alloy specimens were first tested under the strain-controlled monotonic tension, monotonic compression, and cyclic tension–compression conditions. The applied strain and stress rates were set to be 0.002/s and 50 MPa/s, respectively.

3. Results and discussion

3.1. Deformation in monotonic tension and compression tests

Fig. 1 gives the stress–strain curves obtained in the monotonic tensile and compressive tests (where the stress–strain curve for the compressive one is obtained from the absolute values of compressive stress and strain data). Different deformation features are observed as follows: (1) in the monotonic tension, an apparent yielding point with a stress of about 210 MPa occurs, and the tensile ultimate stress is about 270 MPa; (2) in the monotonic compression, the yielding stress is about −50 MPa, but the strain hardening in this case is much more remarkable than that presented in the tension, and the strain hardening rate re-increases after the compressive strain is larger than 5%, as shown in Fig. 1.

Such anisotropic stress–strain responses of AZ31 magnesium alloy presented in the tension and compression tests are mainly caused by its basal plane textures formed during the process of extrusion [2–10]. The basal plane texture makes the *c*-axis of most hexagonal close packed (HCP) grains in the extruded AZ31 magnesium alloy perpendicular to the extrusion direction, and then the extension twinning $\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ in the extruded AZ31 magnesium alloy can be more easily activated in the compression along the extrusion direction than in the tension, which results in a much smaller compressive yielding stress. In the monotonic tension, the extension twinning $\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ and the contraction one $\{10\bar{1}1\}\langle 10\bar{1}2\rangle$ cannot be activated easily, and the plastic yielding can be caused by just the dislocation slipping in the basal slip system. However, the basal plane textures formed in the

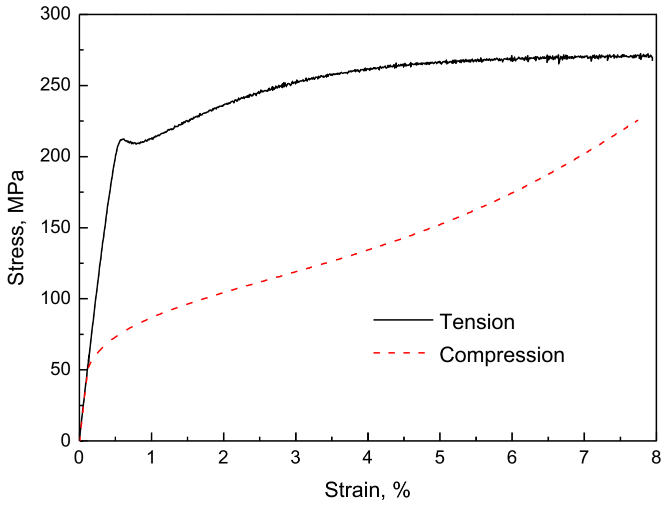

Fig. 1. Monotonic tensile and compressive stress–strain curves.