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Non-proportionally multiaxial cyclic deformation of AZ31 magnesium alloy: Experimental observations

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ABSTRACT

The non-proportionally multiaxial cyclic deformation of extruded AZ31 magnesium alloy with a hexagonal close-packed (HCP) crystal structure is investigated at room temperature by performing the strain- and stress-controlled axial-torsional cyclic tests with different loading paths and using thin-walled tubular specimens. The cyclic hardening/softening and multiaxial ratchetting of the AZ31 alloy are discussed. The AZ31 alloy shows significant cyclic hardening in both axial and torsional stress-strain responses. An additional softening occurs in the axial response, while an additional hardening presents in the torsional one under the multiaxial (i.e., combined axial-torsional) cyclic loading conditions. The multiaxial ratchetting mainly occurs in the direction of non-zero mean stress, and the ratchetting strain greatly depends on the shapes of multiaxial loading paths. The traditional equivalent stress-strain responses cannot reasonably characterize the multiaxial cyclic ones of the AZ31 alloy, since different mechanisms of plastic deformation are involved in the axial and torsional deformations. The axial and torsional stress-strain responses should be discussed separately.

1. Introduction

In recent years, as a kind of lightest metals, the magnesium alloys have been widely used in engineering structures and devices which are often subjected to a cyclic loading. The study on the cyclic deformation of magnesium alloys is very important in the design and reliability assessment of such components and devices. Thus, it is extremely necessary to experimentally investigate the uniaxial and multiaxial cyclic deformation of magnesium alloys, and then a suitable constitutive model can be established to predict their cyclic stress-strain responses.

It is well-known that a strong basal texture might be formed during the manufacture of extruded magnesium alloys, and the c-axes of a majority of grains are perpendicular to the extrusion direction. During the axial tension of the extruded magnesium alloy, the dislocation slipping in the basal $<a>$ slip system can be activated, and the tensile plastic deformation is controlled by the dislocation slipping for small deformation. However, in the axial compressive case, the tensile twinning $\{10\bar{1}2\}<10\bar{1}1>$ can be activated easily due to its lower critical resolved shear stress (CRSS), and the compressive plastic deformation is dominated by the mechanical twinning. The tensile stress-strain curves of extruded magnesium alloy possess a normal concave-down shape with higher yielding stress due to the dislocation slipping mechanism, while the compressive ones are partially concave-up and followed by a S-shaped hardening segment due to the twinning mechanism [1–6]. Besides the dislocation slipping and twinning, detwinning also occurs in the twinned regions, which results in a S-shaped stress-strain curve in the subsequent tensile part, as observed by [6–8] in the cyclic tensile-compressive tests of the extruded magnesium alloy.

For the cyclic deformation of the extruded magnesium alloys, most of the existing experiments [8–16] are performed under a strain-controlled cyclic loading condition. It is found that in the symmetrical strain-controlled cyclic tensile-compressive tests of the extruded magnesium alloys, the asymmetric stress-strain hysteresis loops with the positive mean stress occur since the different mechanisms of plastic deformation are activated in the tensile and compressive loading. Moreover, the cyclic hardening in the compressive direction is more obvious than that in the tensile one. The anisotropic cyclic hardening of the extruded magnesium alloy is caused by the residual twins, which cannot be completely detwinned and will be accumulated with the increasing number of cycles, as commented by [16]. Chen et al. [17] and Begum et al. [18] further concluded that the asymmetry of stress-strain hysteresis

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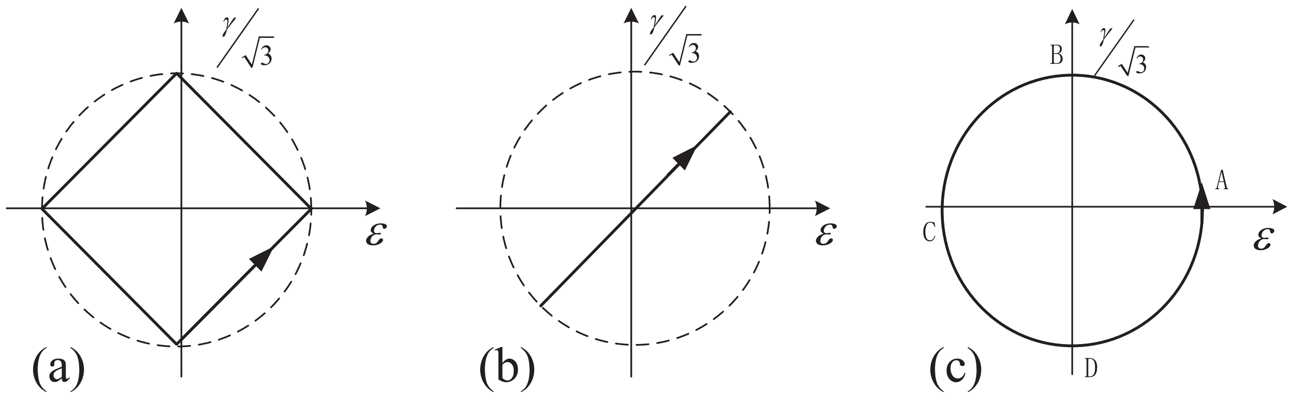

Fig. 1. Loading paths used in the multiaxial strain-controlled cyclic tests: (a) rhombic; (b) linear and (c) circular paths.

loops was more remarkable with the increase of strain amplitude and the decrease of strain ratio.

Several researchers discussed the uniaxial cyclic deformation of the magnesium alloys under the stress-controlled loading conditions. Zhang et al. [19–21] studied the effects of the extrusion ratio, annealing treatment and specimen's orientation on the uniaxial ratchetting of the extruded AZ61A magnesium alloy. Since the stress levels used in [19–21] were specifically prescribed so that no twinning occurred during the cyclic loading, the obtained ratchetting of the AZ61A alloy was similar to that observed in the body-centered cubic (BCC) and face-centered cubic (FCC) metals. Lin et al. [22] investigated the effects of the stress rate, mean stress and stress amplitude on the uniaxial ratchetting and fatigue failure of the extruded magnesium alloy. However, no twinning and detwinning were involved there. Xiong et al. [23] found that, in the stress-controlled cyclic tests of the ZK60 magnesium alloy with the activation of twinning and detwinning, a remarkable cyclic hardening occurred and the stress-strain hysteresis loops became more symmetric with the increasing number of cycles. Kang et al. [24] discussed the effect of the mean stress on the uniaxial ratchetting of the AZ31 magnesium alloy and then revealed the evolution features of ratchetting by considering different mechanisms of plastic deformation (i.e., dislocation slipping, twinning and detwinning). However, the above-referred literature only investigated the uniaxial ratchetting of the extruded magnesium alloys.

Recently, a few experiments were performed to observe the multiaxial cyclic deformation of the extruded magnesium alloys under strain-controlled axial-torsional cyclic loading conditions. For example, Bentachfine et al. [25] studied the biaxial fatigue of a magnesium-lithium alloy by performing some non-proportionally axial-torsional cyclic tests, and concluded that the fatigue life of magnesium-lithium alloy depended on the phase angle between the axial and torsional loads. Zhang et al. [26] observed the occurrence of the mechanical twinning in the regions far away from the fatigue crack. Albinmousa et al. [15,16] found that the stress-strain hysteresis loops of the extruded magnesium alloy were symmetric in the cyclic shear tests, which was different from that observed in the cyclic tensile-compressive ones; however, in the combined axial-torsional cyclic tests, the hysteresis loops became asymmetric again due to the interaction between the dislocation slipping and twinning. It should be noted that, the existing multiaxial cyclic deformation experimental results of the magnesium alloys are mainly obtained in the strain-controlled cyclic tests, the data of multiaxial ratchetting in the stress-controlled cyclic tests are not available yet.

Therefore, in this work, the multiaxial cyclic deformation (including the multiaxial ratchetting) of the extruded AZ31 magnesium alloy is investigated by performing a series of multiaxial cyclic tests with different loading paths at room temperature. The multiaxial ratchetting of the alloy and its dependences on the applied mean stress, stress amplitude and loading path are discussed. Some significant conclusions are obtained.

2. Experimental procedure

The experimental material used in this work is an extruded AZ31 magnesium alloy. Its chemical composition is: Al, 3.05%; Zn 0.82%; Mn, 0.40% and Mg as balance. The thin-walled tubular specimens with an outer diameter of 16 mm, inter diameter of 13 mm and gage length of 20 mm are used in the tests. The experiments are conducted with MTS809 machine at room temperature. The axial and torsional strains are measured using a MTS 632.68F multiaxial extensometer.

In the symmetrical multiaxial strain-controlled cyclic tests, the applied strain rate is 0.002/s and the loading paths shown in Fig. 1 are used. The first two paths are circumscribed by the circular path as shown in Fig. 1. The axial and equivalent torsional strains are denoted as ε and $\gamma/\sqrt{3}$, respectively. In the asymmetrical multiaxial stress-controlled cyclic tests, the applied stress rate is 50 MPa/s, and five loading paths (i.e., a circular path and its inscribed ones) shown in Fig. 2 are used. To compare with the uniaxial ratchetting of the AZ31 magnesium alloy observed by Kang et al. [24], non-zero mean stress is set only in the axial direction, and the mean shear stress is zero for all the loading paths as shown in Fig. 2. The axial and equivalent shear stresses are denoted as σ and $\sqrt{3}\tau$, respectively.

To describe the stress-strain responses of the material in the multiaxial strain-controlled cyclic tests, the responding axial stress amplitude σ_{a} and mean stress σ_{m} defined as Eqs. (1) and (2) respectively, are used in the figures. Here, the σ_{max} and σ_{min} are the maximum and minimum axial stresses for each cycle, respectively. In the torsional direction, similar definitions, i.e., Eqs. (3) and (4), are employed for the responding equivalent shear stress amplitude τ_{ea}, mean equivalent shear stress τ_{em}, and maximum and minimum shear stresses for each cycle, i.e., τ_{max} and τ_{min}.

$$\sigma_a = \frac{1}{2}(\sigma_{max} - \sigma_{min}) \tag{1}$$

$$\sigma_m = \frac{1}{2}(\sigma_{max} + \sigma_{min}) \tag{2}$$

$$\tau_{ea} = \frac{1}{2}(\sqrt{3}\tau_{max} - \sqrt{3}\tau_{min}) \tag{3}$$