Journal of Alloys and Compounds 509 (2011) 6838–6843

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Uniaxial ratcheting and low-cycle fatigue failure behaviors of AZ91D magnesium alloy under cyclic tension deformation

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ARTICLE INFO

Article history:
Received 19 February 2011
Received in revised form 14 March 2011
Accepted 19 March 2011
Available online 29 March 2011

Keywords:
AZ91D magnesium alloy
Uniaxial ratcheting
Cyclic tension
Fatigue life

ABSTRACT

Uniaxial ratcheting and low-cycle fatigue failure behaviors of hot-rolled AZ91D magnesium alloy were studied by uniaxial cyclic stress-controlling tension deformation experiments. The effects of stress amplitude, mean stress and stress rate on the uniaxial ratcheting response and fatigue life of the hot-rolled AZ91D magnesium alloy were analyzed. Results show that (1) the ratcheting strain and ratcheting strain rate of the hot-rolled AZ91D magnesium alloy both increase with the increase of stress amplitude or mean stress; (2) increasing stress rate will decrease the ratcheting strain and ratcheting strain rate of the hot-rolled AZ91D magnesium alloy; (3) the increase of stress amplitude and mean stress can both reduce the fatigue life of the hot-rolled AZ91D magnesium alloy, while the fatigue life will be prolonged with the increase of stress rate.

1. Introduction

Due to their low density, magnesium alloys are predestined for light-weight constructions of components for the automotive industry, such as the panelling, covering plates, sheets, gearbox housings, dashboards, etc. Magnesium alloys have an excellent machinability in terms of metal removal rates and low tools wear. Because of its low corrosion resistance, magnesium is only suitable in an alloyed form. The use of magnesium alloys in transportation vehicles involves unavoidably cyclic deformations and fatigue as the parts in the vehicles undergo cyclic stresses [1–4]. In materials and structures subjected to a cyclic stressing with non-zero mean stress, a cyclic accumulation of inelastic deformation will occur if the applied stress is high enough (ensuring that yielding occurs), which is called ratcheting or the ratcheting effect (some researchers also called it cyclic creep) [5–8]. Ratcheting effect produces not only undesirably large deformations but also fatigue damage in the material. Ratcheting is one of the important factors that should be considered in the design of such structural components. Therefore, it is necessary to evaluate the ratcheting behavior of magnesium alloys.

Over two decades, much effort has been addressed to the ratcheting behaviors of metal materials [9–16]. Uniaxial ratcheting and failure behaviors of SS304 stainless steel and 25CDV4.11 steel were experimentally studied by Kang et al. [9,10], they found that for SS304 steel subject to the uniaxial stress cycling, fatigue life does not decrease monotonically with tensile mean stress but may increase or decrease, depending on the applied stress amplitude, mean stress and stress ratio. Yang et al. [11] and Chen et al. [12] observed the uniaxial and multiaxial ratcheting of 63Sn/37Pb solder alloy at room temperature, and the results showed that the ratcheting strain increased continuously at a relatively higher rate in each cycle due to a cyclic softening effect, which is different from that of stainless steel. Yaguchi and Takahashi [13], Kang [14] and Chen et al. [15] discussed the time-dependent ratcheting of 63Sn/37Pb solder alloy, modified 9Cr–1Mo steel and SiC particulate reinforced 6061Al alloy composites in cyclic stressing with various hold-times at peak/valley stress points and different stress rates, respectively. Kang et al. [16] observed the dependence of ratcheting of SS304 steel on stress rate, loading chart, peak/valley stress hold and non-proportionally multiaxial loading path at room and high temperatures. Chen et al. [17] studied the ratcheting and fatigue properties of high-nitrogen steel X13CrMnMoN18-14-3 under cyclic loading, and the effects of stress amplitude, mean stress, loading history and stress rate on the ratcheting behavior were analyzed. The uniaxial time-dependent ratcheting of polyester resin and glass fiber reinforced polyester resin matrix composites was observed by stress-controlled cyclic tension–compression with non-zero tensile mean stress and tension–tension tests at room temperature [18]. Wang et al. [21] studied the uniaxial ratcheting and fatigue behavior of low-temperature sintered silver films at room and high temperature, and particular attention

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0925-8388/$ – see front matter
doi:10.1016/j.jallcom.2011.03.129

Table 1
Chemical compositions of AZ91D magnesium alloy plate (in wt.%).

Al	Zn	Mn	Si	Cu	Ni	Fe	Mg
8.5–9.5	0.45–0.90	0.17–0.4	≤0.05	≤0.025	≤0.001	≤0.004	Bal.

was paid to the influence of ratcheting on fatigue. Zhang et al. [22–24] studied the uniaxial and multiaxial ratcheting behavior of polyteterafluoroethylene (PTFE) at room and elevated temperature, and established a constitutive model for cyclic compressive ratcheting deformation of PTFE with stress rate effects. Lin et al. [25] studied the uniaxial ratcheting behavior of anisotropic conductive adhesive film under cyclic tension, and the effects of mean stress, stress amplitude and loading history on the ratcheting response of ACF material were discussed in detail.

In this study, the uniaxial ratcheting behavior of hot-rolled AZ91D magnesium alloy was studied under asymmetrical uniaxial cyclic loadings. The effects of stress amplitude, mean stress and stress rate on the ratcheting response of hot-rolled AZ91D magnesium alloy were discussed in details.

2. Experiments and results

The commercial hot-rolled AZ91D magnesium alloy plate was used in this investigation. The compositions of the material are shown in Table 1. Dog-bone flat specimens with a rectangular cross section of 2 mm × 3 mm and a gauge length of 30 mm were machined along the rolled direction. The cyclic stress-controlling tension deformation experiments were conducted on a micro uniaxial fatigue testing system (EUT1020) made by CARE Measure & Control Co., Ltd. [26] at room temperature. The cyclic ratcheting and low-cycle fatigue failure tests were carried out under stress-controlling mode at varied stress amplitude, mean stress and stress rate, and the detailed loading conditions are listed in Table 2.

Table 2
Loading conditions of uniaxial cyclic tension experiments for AZ91D magnesium alloy plate.

Specimen ID	Mean stress (σ_m, MPa)	Stress amplitude ($\Delta\sigma/2$, MPa)	Stress rate (MPa/s)
SP1	150	75	50
SP2	150	100	50
SP3	150	125	50
SP4	100	125	50
SP5	125	125	50
SP6	125	125	100
SP7	125	125	10

3. Results and discussion

Typical sine wave loading and stress–strain curves of the uniaxial ratcheting test on AZ91D magnesium alloy (under stress amplitude of 75 MPa, stress rate of 50 MPa/s, and mean stress of 150 MPa) are shown in Fig. 1a and b, respectively. AZ91D magnesium alloy was tested under asymmetrical stress-controlled cycling under room temperature. From Fig. 1b, it can be seen the hysteresis loops in ratcheting tests under axial stress control are not closed at the beginning, which will result in the ratcheting response of the material. With the increasing of cycle number, the initial closed

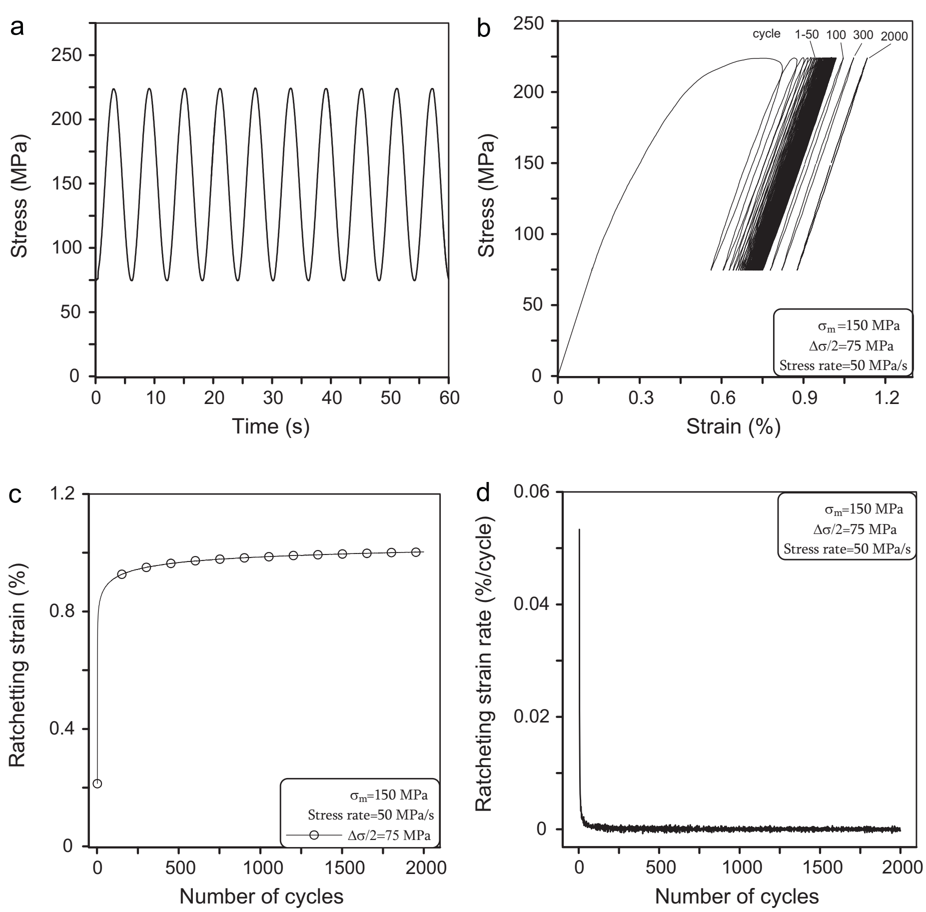

Fig. 1. Uniaxial ratcheting and low-cycle fatigue test of AZ91D magnesium alloy: (a) stress-controlling diagram; (b) stress–strain curve; (c) ratcheting strain evolution; (d) ratcheting strain rate.

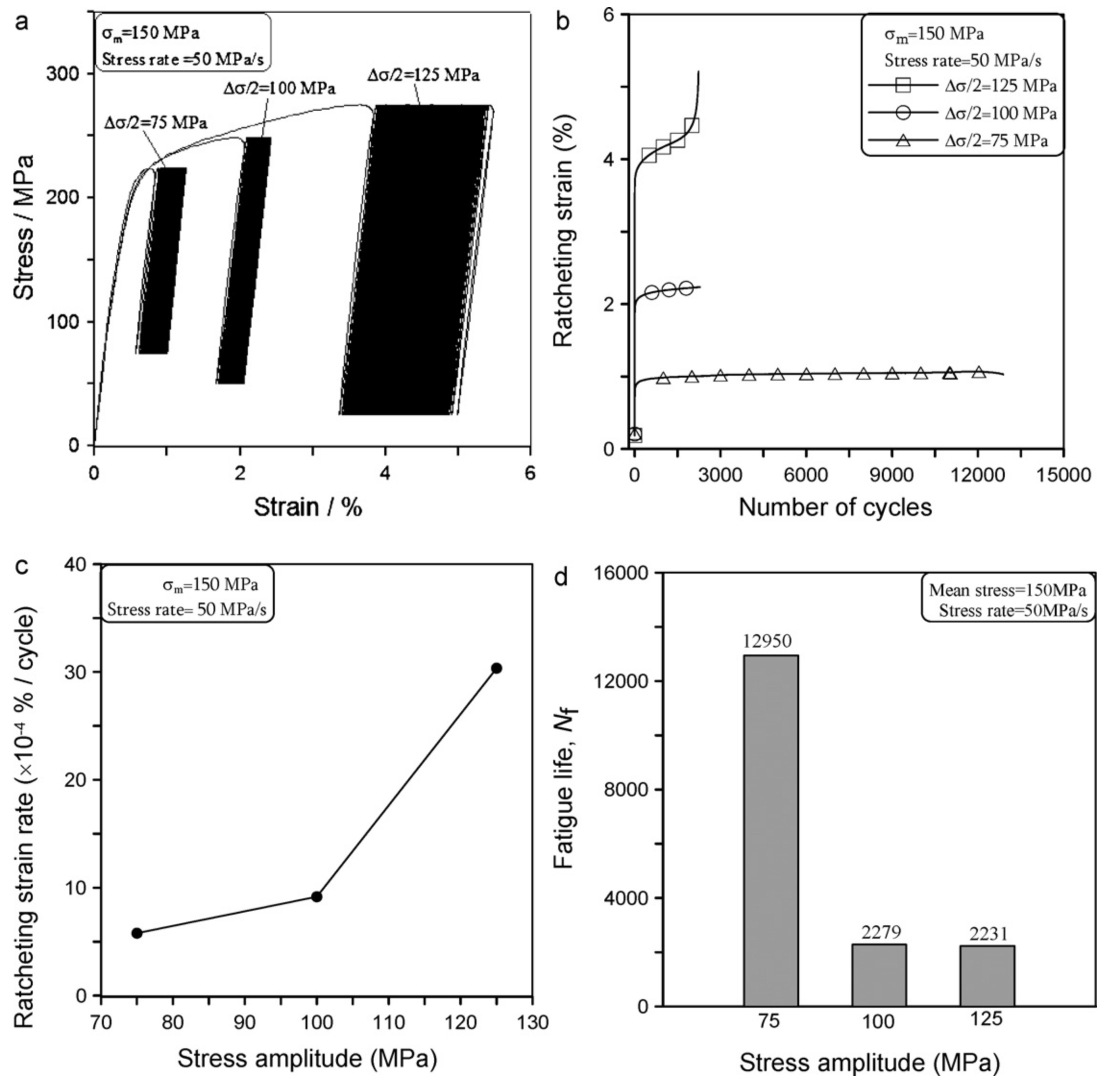

Fig. 2. Uniaxial ratcheting and low-cycle fatigue tests with the constant mean stress of 150 MPa and stress rate of 50 MPa/s: (a) stress–strain curve; (b) ratcheting strain evolution; (c) ratcheting strain rate evolution; (d) fatigue life.

hysteresis loops becomes more and more obvious. Therefore, the following definitions of the axial ratcheting strain and ratcheting strain rate (i.e., the increment of ratcheting strain in each cycle) in a cycle are introduced:

$$\varepsilon_r = \frac{\varepsilon_{\max} + \varepsilon_{\min}}{2} \quad (1)$$

$$\dot{\varepsilon}_r = \frac{d\varepsilon_r}{dN} \quad (2)$$

where $\varepsilon_{\max}$ and $\varepsilon_{\min}$ are the maximum and minimum of the axial strain in a cycle, respectively, and N is the number of cycles. The ratcheting strain for each cycle is plotted in Fig. 1c as a function of the number of cycles. Obviously, the ratcheting strain is increasing with the increase of cycles and tends to be a constant after certain cycles, which illustrates that the hot-rolled AZ91D magnesium alloy shows visible cyclic hardening feature. Fig. 1(c) shows that the axial strain evolution can be divided into two stages: transient and steady state. The first stage is the shortest and characterized by an initial sharp increase in ratcheting strain. The second stage has the longest duration and shows almost constant rate of strain accumulation. Generally, the axial strain evolution should include three stages: transient, steady state and tertiary [19,20]. In this case, only 2000 cycles are shown in Fig. 1c, and the final (tertiary) stage is not obvious. In fact, during the final stage, an accelerated increase in ratcheting strain will appear and lead to ultimate failure of the specimens. The typical relationship between the ratcheting strain rate and number of cycles is shown in Fig. 1d, which can reflect the increasing velocity of the ratcheting strain with the increase of cycle numbers. The ratcheting strain rate rapidly decreases firstly, and then exhibits a relatively stable and small value (about 5.78×10^{-5} %/cycle for this case).

3.1. *Effects of stress amplitude on uniaxial ratcheting behaviors and fatigue life*

In order to understand the ratcheting sensitivity to the stress amplitude for the hot-rolled AZ91D magnesium alloy, some uniaxial cyclic tension experiments were conducted with constant mean stress of 150 MPa, stress rate of 50 MPa/s and different stress amplitude, as shown in Table 2 (specimens SP1–SP3). Fig. 2 summarizes the effects of the stress amplitude on uniaxial ratcheting and low-cycle fatigue failure behaviors of hot-rolled AZ91D magnesium alloy under mean stresses of 150 MPa and stress rate of 50 MPa/s. Obviously, the stress amplitude has a great influence on the uniaxial ratcheting behaviors of AZ91D magnesium alloy. When the stress amplitude is increased, the ratcheting strain increases correspondingly, as shown in Fig. 2b. Furthermore, the tertiary stage of the

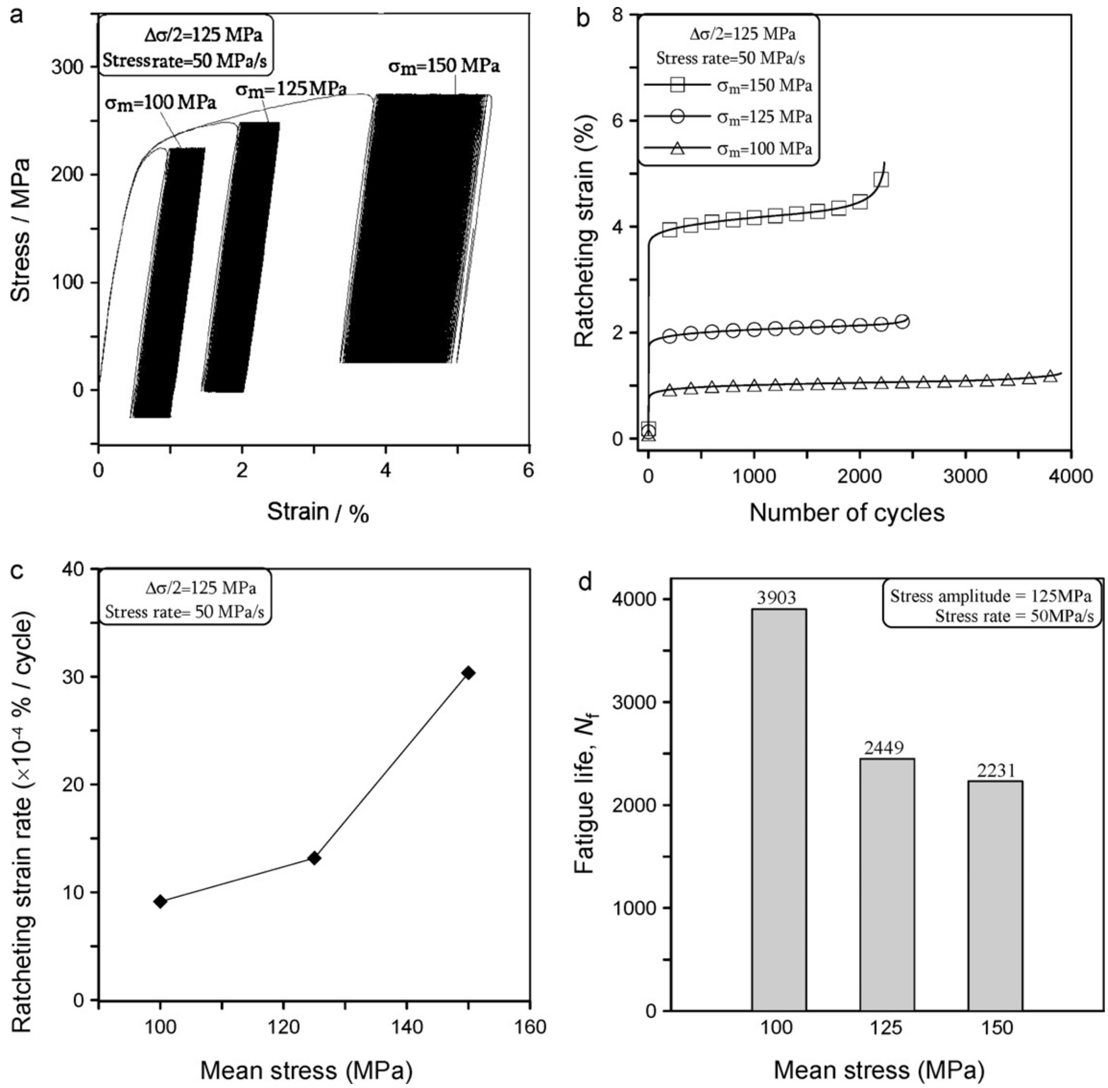

Fig. 3. Uniaxial ratcheting and low-cycle fatigue tests with the constant stress amplitude of 125 MPa and stress rate of 50 MPa/s: (a) stress–strain curve; (b) ratcheting strain evolution; (c) ratcheting strain rate evolution; (d) fatigue life.

ratcheting axial strain evolution is not obvious for the cases with stress amplitudes of 100 MPa and 75 MPa. The ratcheting strain rates in steady state changes greatly with the variations of the stress amplitude, as shown in Fig. 2c. When the stress amplitude is 75 MPa, the ratcheting strain rates is only about 5.78×10^{-5} %/cycle. When the stress amplitude is 125 MPa, the ratcheting strain rates is rapidly increased as approximate 3.03×10^{-4} %/cycle. So, the effects of the stress amplitude on the ratcheting strain rates are significant. Fig. 2d shows the effects of the stress amplitude on the low-cycle fatigue life are significant, but there is no obvious difference between the cases with stress amplitudes of 100 MPa and 125 MPa.

3.2. Effects of mean stress on uniaxial ratcheting behaviors and fatigue life

In this section, the uniaxial ratcheting sensitivity to the mean stress for the hot-rolled AZ91D magnesium alloy is discussed. Some uniaxial cyclic tension experiments, as shown in Table 2 (specimens SP3–SP5), were conducted under a stress amplitude of 125 MPa, stress rate of 50 MPa/s and different mean stress. Fig. 3 shows the measured results from the uniaxial ratcheting and low-cycle fatigue failure tests with the effects of mean stress taken into account. From Fig. 3, it can be found that the mean stress has a great influence on the uniaxial ratcheting strain of the hot-rolled AZ91D magnesium alloy. Obviously, the increase of mean stress will result in the rapid increase of the uniaxial ratcheting strain. Similarly, the tertiary stage of the ratcheting axial strain evolution is not obvious for the cases of mean stresses of 100 MPa and 125 MPa. Furthermore, when the mean stress is increased from 100 MPa to 150 MPa, the ratcheting strain rate will triple the original value. Also, the low-cycle fatigue life is greatly influenced by the mean stress, as shown in Fig. 3d.

3.3. Effects of stress rate on uniaxial ratcheting behaviors and fatigue life

In order to illustrate the uniaxial ratcheting sensitivity to the stress rate, a series uniaxial cycle deformation tests, as shown in Table 2 (specimens SP5–SP7), were carried out with the constant amplitude of 125 MPa and mean stress of 125 MPa. The experimental results are given in Fig. 4. In order to clearly describe the ratcheting behavior under different experimental conditions, only 2000 cycles are given in Fig. 4. Obviously, the effects of the stress

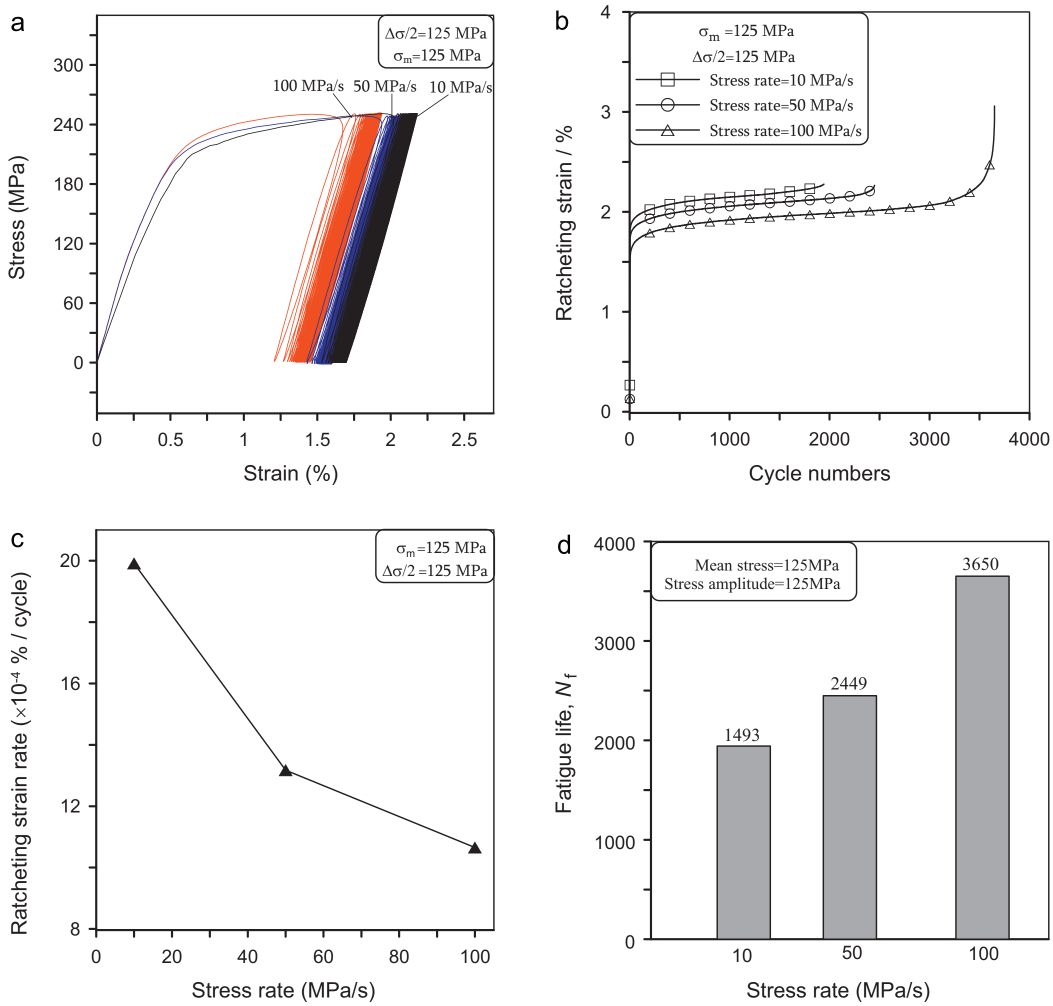

Fig. 4. Uniaxial ratcheting and low-cycle fatigue tests with the constant stress amplitude of 125 MPa and mean stress of 125 MPa: (a) stress–strain curve; (b) ratcheting strain evolution; (c) ratcheting strain rate evolution; (d) fatigue life.

rate on the ratcheting strain (Fig. 4b) and its rate (Fig. 4c) are significant. The uniaxial ratcheting strain and its rate both decrease with the increase of stress rate, which shows that ratcheting strain rate is highly sensitive to the applied cyclic stress rate. The low-cycle fatigue life increases with the increase of the stress rates. This is because the higher stress rate results in the smaller ratcheting strain, thus the less fatigue damage and the longer fatigue life.

4. Conclusions

The effects of stress amplitude, mean stress and stress rate on the uniaxial ratcheting and low-cycle fatigue failure behaviors of hot-rolled AZ91D magnesium alloy were investigated. Some important conclusions can be made as follows.

(1) The stress amplitude has a great influence on the uniaxial ratcheting strain. When the stress amplitude is increased, the ratcheting strain rapidly increases.
(2) The mean stress also has a great influence on the uniaxial ratcheting behavior. When the mean stress is increased, both the ratcheting strain and ratcheting strain rate increase correspondingly.
(3) The ratcheting strain and ratcheting strain rate both decrease with the increase of stress rate.
(4) The low-cycle fatigue life decreases with the increase of stress amplitude and mean stress. However, the increase of stress rate will prolonged the fatigue life.

Acknowledgements

This work was supported by Sheng-hua Yu-ying Program of Central South University, and the Young Core Instructor from the Education Commission of Hunan Province, China.

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