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Compressive deformation behavior of AZ31 magnesium alloy under quasi-static and dynamic loading

ZHAO Feng(赵 峰)[1], LI Yu-long(李玉龙)[1], SUO Tao(索 涛)[1],
HUANG Wei-dong(黄卫东)[2], LIU Jian-rui(刘建睿)[2]

(1. School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072，China;
(2. State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an 710072，China)

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Abstract: Compressive properties of AZ31 alloy were investigated at temperatures from room temperature to 543 K and at strain rates from 10^{-3} to 2×10^{4} s^{-1}. The results show that the compressive behavior and deformation mechanism of AZ31 depend largely on the temperature and strain rate. The flow stress increases with the increase of strain rate at fixed temperature, while decreases with the increase of deformation temperature at fixed strain rate. At low temperature and quasi-static condition, the true stress—true strain curve of AZ31 alloy can be divided into three stages (strain hardening, softening and stabilization) after yielding. However, at high temperature and high strain rate, the AZ31 alloy shows ideal elastic-plastic properties. It is therefore suggested that the change in loading conditions (temperature and strain rate) plays an important role in deformation mechanisms of AZ31 alloy.
Key words: AZ31magnesium alloy; compressive properties; dynamic deformation; strain hardening; strain rate sensitivity

1 Introduction

Magnesium alloys are currently of great potential for application in automobile and aircraft industries, because of their low density which is essential for mass reduction and fuel efficiency[1−2]. In addition, they have other attractive properties such as good castability and machinability, and high specific strength and stiffness[3]. AZ31 and AZ91 alloys (Mg-Al-Zn system) in particular, are most widely used as lightweight structure in automobile and aircraft industry. Since these structural components inevitably undergo impacts or vibrations during their service period, the dynamic mechanical behaviors of the materials should be carefully considered.

The hexagonal close-packed (hcp) structured magnesium alloys exhibit low ductility at room temperature (RT), while at elevated temperature, they are found to have good ductility as well as low strength[4−7]. At RT, the "basal a" slip $\{0001\}\langle 11\bar{2}0\rangle$ is predominant, while at elevated temperatures, the "prism a", "pyramidal a" and $\langle c+a\rangle$ are unlocked[4]. Recently, there are many studies[8−14] on the mechanical characteristics of magnesium alloys at low strain rates and various temperatures. However, investigations on the dynamic mechanical behaviors[15] at various temperatures are hardly found. So, one of the technical challenge for widespread applications of the magnesium alloys is on full understanding of the dynamic deformation mechanics at different temperatures.

The aim of the present work is to investigate the deformation behavior in the compression of AZ31 magnesium alloys over a wide range of strain rates and temperatures, and to evaluate the influence of the loading factors on the plastic deformation behavior.

2 Experimental

2.1 Materials

The cast AZ31 magnesium alloy was supplied by the State Key Laboratory of Solidification Processing in Northwestern Polytechnical University, China. The chemical composition of this alloy is Mg-3.0%Al-1.0%Zn-1.0%Ca-0.4%Mn (mass fraction). In the quasi-static and dynamic tests, the dimensions of the AZ31 specimens are about *d*5 mm×5 mm and *d*2 mm×

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Corresponding author: LI Yu-long; Tel:＋86-29-88494859; E-mail: liyulong@nwpu.edu.cn
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2 mm, respectively.

2.2 Quasi-static tests

The quasi-static compressive strength of the AZ31 magnesium alloy was determined using a CCSS88010 electric universal tension-compression test machine. Specimens were tested at a constant crosshead speed of 0.3, 3 and 30 mm/min, corresponding to the strain rates of 10^{-3}, 10^{-2} and 10^{-1} s^{-1}. During the compression test, mineral oil was used as a lubricant between the sample and the platen. The stiffness of test machine is calibrated and considered during the displacement measurement.

2.3 Dynamic tests

The most widely used approach to measure the dynamic response of materials is the Split-Hopkinson pressure bar (SHPB) (as shown in Fig.1) or compression Kolsky bar. The SHPB system consists of two long steel bar sandwiching a small cylindrical specimen. Both contact surfaces of specimen with the bars were lubricated in order to reduce the effect of friction. When the incident bar is impacted by the striker bar, a compressive stress pulse is generated and propagates along the incident bar to the specimen. This loading pulse results in plastic deformation of the specimen, and then partially propagates through the specimen into the transmission bar as a transmitted pulse. Meanwhile, at the incident bar/specimen interface, the loading pulse is partially reflected back into the incident bar as a reflected pulse. These reflected and transmitted pulses are measured using strain gages placed on the elastic bars. Different strain rates were performed by changing the length striker and the pressure of the gas gun. Based on the elementary theory of one-dimensional elastic wave propagation, the average strain ε_s, strain rate $\dot{\varepsilon}_s$ and stress σ_s of the specimen can be acquired as

$$\dot{\varepsilon}_s(t)=\frac{2C_0}{l_s}\varepsilon_r(t) \tag{1}$$

$$\varepsilon_s(t)=\frac{2C_0}{l_s}\int_0^t\varepsilon_r(t)\mathrm{d}t \tag{2}$$

$$\sigma_s(t)=E\left(\frac{A}{A_s}\right)\varepsilon_t(t) \tag{3}$$

where ε_r and ε_t are the reflected and transmitted strain pulses, respectively; E, A and C_0 denote the elastic modulus, cross-sectional area and longitudinal wave speed of the bars; A_s and l_s are the cross-sectional area and length of the specimen. The history of stress according to Eq.(3) and the history of strain according to Eq.(2) were combined to yield the stress — strain relationship of the specimen.

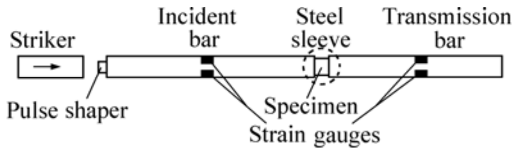

Fig.1 Schematic illustration of Split-Hopkinson pressure bar system

The high temperature SHPB tests were performed using a special designed system with a heating furnace. While the specimen is being heated, the elastic bars are not in contact with the specimen but remain very close to RT. When the appointed temperature is achieved, the incident and transmission bars are brought into contact with the specimen by a synchronical assembly system right before the stress pulse reaches the far end of the incident bar. Details of the synchronical assembly technique can be found in Ref.[16].

3 Results

3.1 Compressive properties at RT

The compression tests were performed at temperatures of RT, 373 K, 473 K and 543 K at strain rates of 1×10^{-3}, 1×10^{-2}, 1×10^{-1}, 5×10^{3}, 1×10^{4} and 2×10^{4} s^{-1}. Fig.2 shows the compression curves of true stress vs true strain for AZ31 Mg alloy at RT under various strain rates. At RT, the AZ31 Mg alloy shows the typical mechanical characteristics of low ductile material. All the compression tests were interrupted because of the sample fracture with an angle of 45° with respect to the loading direction. It can be seen that AZ31 Mg alloy exhibits strain rate sensitivity under uniaxial compressive loading. Both strength and ductility increase due to strain rate increasing. The yield strength increases from 78 MPa ($\dot{\varepsilon}=1\times10^{-1}$ s^{-1}) to 175 MPa ($\dot{\varepsilon}=2\times10^{4}$ s^{-1}), the peak strength from 222 MPa ($\dot{\varepsilon}=1\times10^{-1}$ s^{-1}) to 261 MPa ($\dot{\varepsilon}=2\times10^{4}$ s^{-1}), and the compressive fracture strain

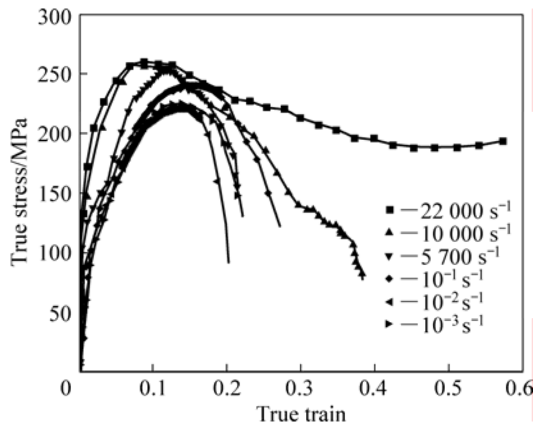

Fig.2 True stress vs true strain curves of AZ31 Mg alloy under various strain rates at RT

increases from 17.8% ($\dot{\varepsilon}$=1×10^{-1} s^{-1}) to 38% ($\dot{\varepsilon}$=2×10^{4} s^{-1}). Fig.2 indicates that the flow curves show strong strain hardening after yielding and the peak point are followed by a softening of up to 50% ($\dot{\varepsilon}$=1×10^{-1} s^{-1}) or 20% ($\dot{\varepsilon}$=2×10^{4} s^{-1}) with respect to the peak stress. In these testing conditions, samples fractured quickly after softening. Fig.2 shows that the strain corresponding to the peak stress decreases with the increase of strain rate, indicating that AZ31 Mg alloy exhibits stronger strain hardening before yielding at higher strain rates.

3.2 Compressive properties at elevated temperatures

Fig.3 shows the compression true stress vs true strain curves of AZ31 Mg alloy at elevated temperatures under various strain rates. It can be seen that AZ31 Mg alloy exhibits enhanced strain rate sensitivity at elevated temperatures, especially at 543 K. The peak stress decreases with increasing temperature under fixed strain rate and decreases with decreasing strain rate at a fixed temperature. The strain hardening property of AZ31Mg alloy gradually weakens with increasing the testing temperature. There is no significant strain hardening at temperature higher than 473 K (Fig.3(b)), suggesting that elevated temperature could decrease strain hardening capability of AZ31 Mg alloy. It is evident that the fracture strain depends greatly on the strain rate and temperature. The fracture strain increases both with increasing strain rate and increasing testing temperature. In Figs.3(b) and 3(c), it can be seen that there is no obvious peak after yielding on flow curves. The AZ31 Mg alloy has the capability of large uniform deformation under uniaxial compression at 543 K.

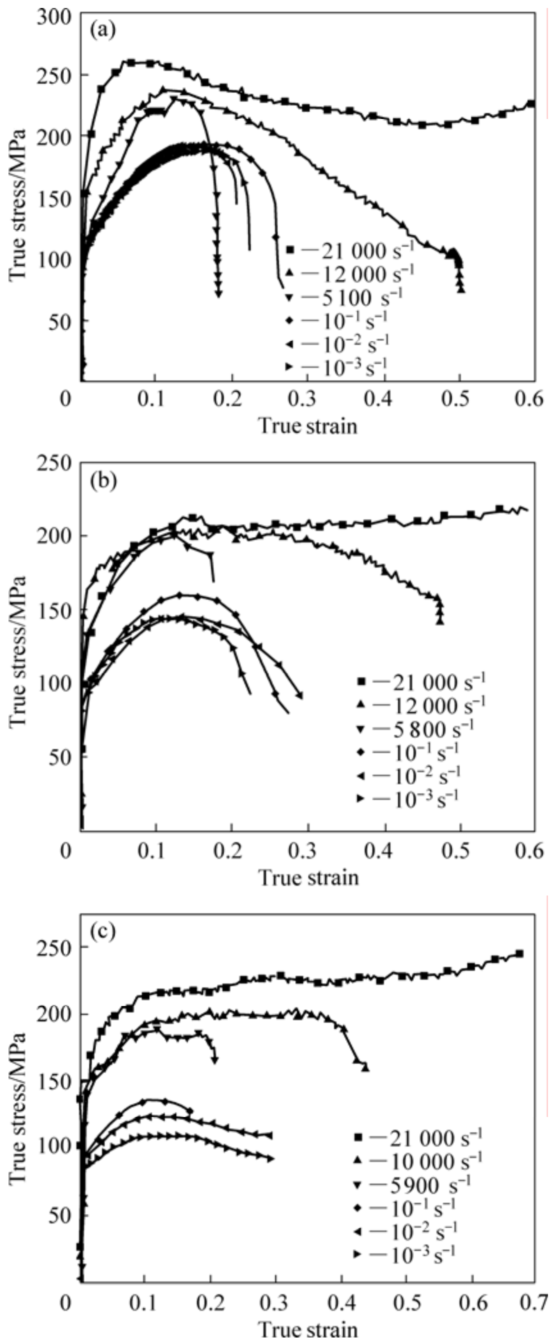

Fig.3 True stress vs true strain curves of AZ31 Mg alloy under various strain rates at 373 K (a), 473 K (b) and 543 K (c)

4 Discussion

4.1 Temperature-dependent plastic deformation

Fig.4 shows the flow curves of AZ31 Mg alloy at RT and 543 K at strain rates of 1×10^{-2} and 2×10^{4} s^{-1}. At RT, the flow curves exhibit peak stress, 262 MPa (2×10^{4} s^{-1}) and 240 MPa (1×10^{-2} s^{-1}), and obvious softening after peak. In contrast, at 543 K, there is no evident peak or softening for the curves. The difference of the flow curves of AZ31 Mg alloy at various temperatures is due to the difference of plastic deformation mechanism. Magnesium alloys have HCP crystalline structure. At RT, magnesium alloys have only two independent slip systems that contribute to plastic deformation. The plastic flow of AZ31 Mg alloys largely depends on deformation twining in polycrystalline Mg alloy to compensate for the insufficiency of independent slip systems. The magnesium alloys will exhibit strain

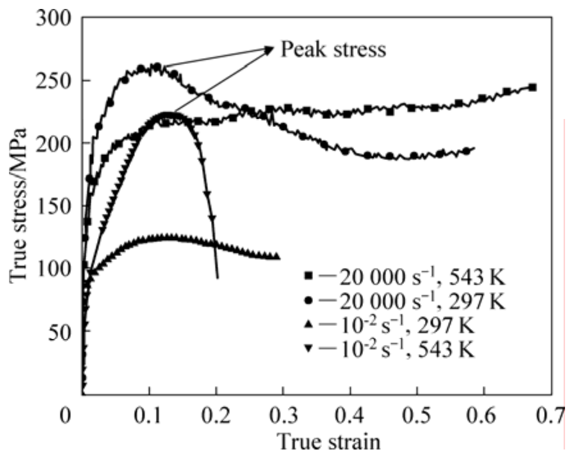

Fig.4 Stress—strain curves of AZ31 Mg alloy at different strain rates and temperatures

hardening behaviour during plastic deformation if twining is produced. In contrast, at elevated temperatures, besides the two basic slip systems, the “prism” and “pyramidal” slip systems are activated too. The main plastic deformation mechanism is slip at elevated temperatures. As a result, the AZ31 Mg alloy has relatively large plastic flow with lower strain hardening at elevated temperatures.

Fig.5 illustrates the peak stress variations as a function of temperature at different strain rates for the AZ31 Mg alloy. The increasing temperature decreases the compressive strength but increases the ductility of the AZ31 Mg alloy. The peak stress decreases with increasing temperature at the constant strain rate, while increases with increasing strain rate at a fixed temperature. But at the strain rate of 2×10^4, the peak stresses are almost the same as the temperature decreases from 543 K (213 MPa) to 473 K (215 MPa), which may suggest that the effect of temperature on the mechanical behaviour of AZ31 Mg alloy is depressed at high strain rates. However, this deduction needs more investigation.

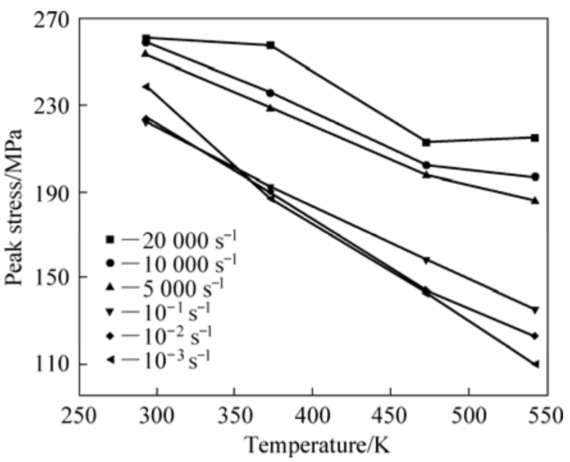

Fig.5 Relationship between peak stress and temperature of AZ31 Mg alloy at various strain rates

4.2 Strain rate-dependent plastic deformation

The strain rate dependence of the compressive response of AZ31 Mg alloy is shown in Fig.2 and Fig.3, which present flow curves under quasi-static and dynamic loading at different temperatures. Clearly, AZ31 alloy is strain rate sensitive and the strain rate sensitivity increases with increasing temperature. Fig.6 illustrates the strain rate effect for the AZ31 Mg alloy. The peak stress increases with increasing strain rate at a fixed temperature and the strain rate sensitivity increases from 0.001 8 (RT) to 0.004 9 (543 K) with increasing temperature. In general, the strength of the test materials will increase with the increasing strain rate. This is because the plastic deformation of test materials needs a certain time to accomplish (just like forming deformation twinning). High strain rate means the time for plastic deformation is very short. As a result, there is no enough time for plastic deformation and the deformation resistance force generated by the nature of the material could not be reduced, leading to strength increase with increasing strain rate. At RT, the primary deformation mechanism of AZ31 Mg alloy is deformation twins. But at elevated temperature, the plastic deformation of AZ31 Mg alloy mainly depends on slip. The change of the deformation mechanism at various temperatures determines the strain rate sensitivity of AZ31 Mg alloy.

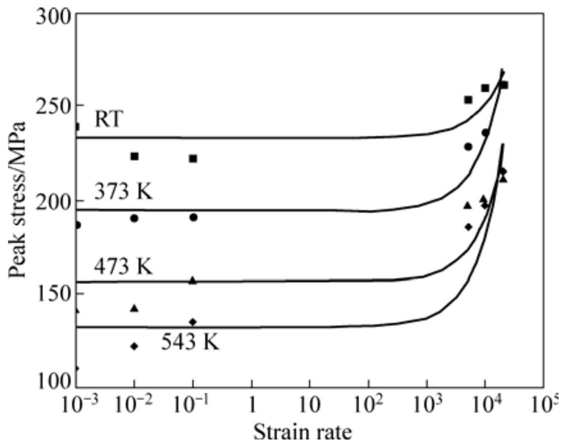

Fig.6 Relationship between peak stress and strain rates of AZ31 Mg alloy at various temperatures

5 Conclusions

1) Both the strength and ductility of AZ31 Mg alloy increase with increasing strain rate. At RT, the stress—strain curves show strong strain hardening after yielding and softening after the peak stress is achieved.

2) The peak stress decreases with increasing temperature at a fixed strain rate. The AZ31 Mg alloy exhibits higher strain rate sensitivity at elevated temperatures, especially at 543K. The change of the deformation mechanism at various temperatures is believed to affect the strain rate sensitivity.

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