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Effect of heating-rate on failure temperature of pre-loaded magnesium alloy

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Abstract: The response and failure of magnesium alloy AZ31 specimens subjected to different pre-loaded-stress levels and heating rates were investigated with a Gleeble−1500 thermo-mechanical material testing system. It is found that the increases of either pre-loaded stresses or heating-rates decrease the failure temperatures of the specimens. The metallographs of the tested specimens were also observed. It is shown that the high heating-rate may cause stronger local thermal inconsistency, which remarkably increases the microdefects and reduces the macroscopic mechanical properties of the material.

Key words: magnesium alloy AZ31; pre-loaded stress; heating rate; failure temperature; local thermal inconsistency

1 Introduction

It is known that the high and rapid increase in temperature may result in a remarkable change of the microstructures of materials[1−3]. The microstructural change may alter the mechanical properties of materials. The investigation on the changes of the microstructures and the mechanical properties of materials with highly and rapidly increasing temperature may help to avoid material failure and provide available information for making use of fast-heating technology[4−6].

The failure of materials and structures caused by the high and rapid increase in temperature are received increasing attention[7−10]. LIU et al[9] investigated the nonlinear softening of aluminum alloy subjected to fast heating. It was found that the differences in heating-rate history may cause differences in both the grain size and the macroscopic mechanical properties of the material, which was accounted for the dynamics of recrystallization. WANG et al[10] conducted a set of tensile tests of low-alloying steel 30CrMnSi subjected to fast heating histories with different heating-rates. The test results showed distinct differences in both the rupture strength and the metallograph of the material. PENG et al[11−14] investigated the effect of heating-rate on the mechanical properties of aluminum alloy LY12 and indicated that the material experiencing higher heating-rate histories possesses lower rupture strength and that the pre-stressed material fails at lower temperature, which was attributed to the increase of microdefects due to the strong local thermal inconsistency at high heating-rate. In this work, a systematic experiment was conducted with a Gleeble−1500 thermo-mechanical material testing system to investigate the effect of heating-rate on the failure temperature of pre-loaded magnesium alloy AZ31 specimens. The metallographs of the tested material were also observed and analyzed.

2 Experimental

A Gleeble−1500 thermo-mechanical material testing system was used to investigate the effect of heating-rate on the failure temperature of pre-loaded magnesium alloy AZ31 specimens (Fig.1). In the experiment, the specimens were heated with direct current by applying an electric voltage directly between the two ends of the specimens. The experimental temperature and the heating rate were measured with a chromel-alumel

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thermocouple welded directly on the surface of the working section and controlled by a computer[14−15]. The tensile stress and the temperature were recorded synchronously with the data acquisition element of the testing system. To investigate the effect of heating-rate on the failure temperature of pre-loaded AZ31 specimens, three different levels of pre-loaded stresses, 50, 100 and 150 MPa, were prescribed, for each of which three different heating-rates, 100, 300 and 500 ˚C/s, were assigned. Namely, the specimens of the AZ31 were firstly preloaded to a prescribed stress level, and then they were heated with one of the three prescribed heating-rates. In order to make clear the effect mechanisms of the heating-rates on the mechanical properties of the pre-loaded AZ31, the metallographs of the tested specimens were observed and analyzed. The samples used for the metallographic observation were cut from the vicinity of the fracture section of tested specimens, eroded in a mixed 2.5% HNO_3, 1.5% HCl and 1% HF solution for 10−20 s, and then cleaned for observation.

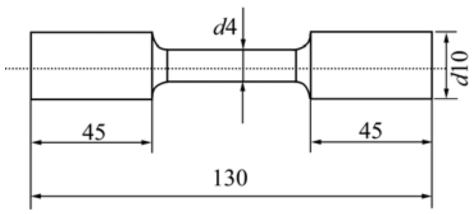

Fig.1 Draft of specimen (Unit: mm)

3 Results and discussion

Fig.2(a) and (b) show the measured relationships between the temperature and time, and the stress and temperature of the specimens subjected to the pre-loaded stress of 50 MPa and heated with three different heating-rates 100, 300 and 500 ˚C/s, respectively. It can be seen from Fig.2(a) that the temperature increases almost linearly at different heating-rates, which shows that the heating-rates are reliably given and controlled. It can also be found from Fig.2(b) that the prescribed pre-loaded stress σ=50 MPa is transitorily maintained before the failure temperature is reached, and then falls rapidly. The failure temperature of the pre-loaded material reduces with the increase of the heating rates (Fig.2(b)). Fig.3(a) and (b) show the measured relationships between the temperature and time, and the stress and temperature of the specimens subjected to the pre-loaded stress of 100 MPa and heated with three different heating-rates, 100, 300 and 500 ˚C/s. It can be seen from Fig.3(a) that the temperature also increases almost linearly at different heating-rates. It can also be found from Fig.3(b) that the prescribed pre-loaded stress σ=100 MPa is also transitorily maintained before the failure temperature is reached. It can be observed that the failure temperature of the pre-loaded material also reduces with the increase of the heating rates (Fig.3(b)). Fig.4(a) shows the variation of the failure temperature against the pre-loaded stress, taking the heating-rate as a parameter. It can be seen that, for a fixed heating-rate, the failure temperature of the pre-loaded material reduces with the increase of the pre-loaded stress due to the softening of the material at an elevated temperature. The variation of the failure temperature against the heating-rate at different pre-loaded stresses is shown in Fig.4(b). Remarkable reduction in the failure temperature can be observed with the increase of the heating-rate, which implies that the heating-rate may play a significant role in the failure of the pre-loaded materials.

Fig.5(a)−(c) shows the metallographs of the specimens subjected to the pre-loaded stress of σ=50 MPa

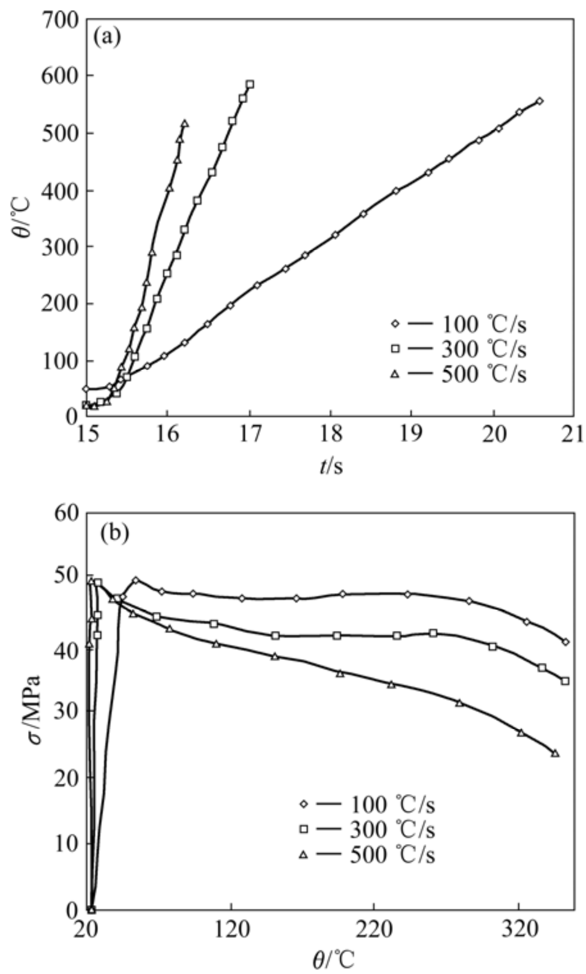

Fig.2 Testing results at different heating rates with σ=50 MPa: (a) Temperature vs time; (b) Stress vs temperature

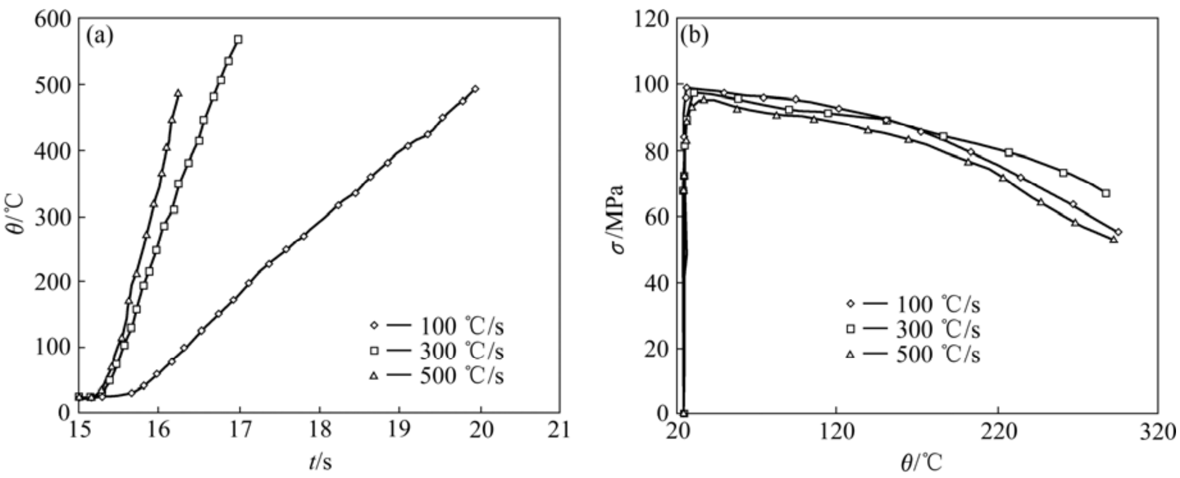

Fig.3 Testing results at different heating rates with σ=100 MPa: (a) Temperature vs time; (b) Stress vs temperature

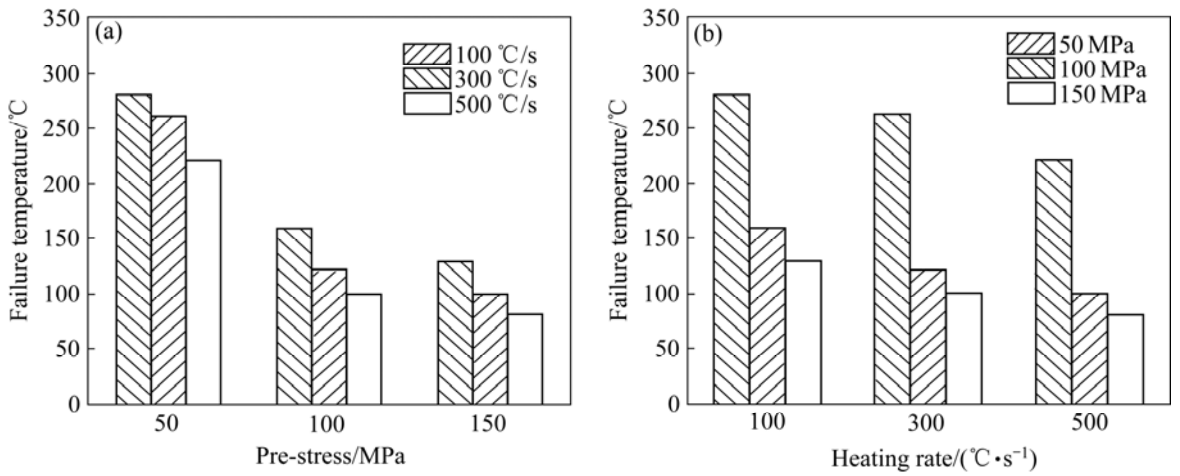

Fig.4 Failure temperatures at different pre-stresses and heating-rates: (a) Failure temperature vs pre-stress; (b) Failure temperature vs heating rates

and the heating-rates of 100, 300 and 500 ˚C/s, respectively. It can be seen from Fig.5(a)−(c) that there are fewer microvoids in the specimen at a lower heating-rate, and the microvoids will develop in both density and size with the increase of the heating-rate. Fig.6(a)−(c) show the metallographs of the specimens subjected to the pre-loaded stress of σ=100 MPa and the heating-rates of 100, 300 and 500 ˚C/s, respectively. It can also be seen from Fig.6(a)−(c) that there are more microvoids in the specimen with the increase of the heating rates. Fig.7(a)−(c) show the metallographs of the specimens subjected to the pre-loaded stress of σ=150 MPa and the heating-rates of 100, 300 and 500 ˚C/s, respectively. It can also be seen from Fig.7(a)−(c) that there are more microvoids in the specimen with the increase of the heating rates. An identical characteristic in Figs.5−7 is that the microvoids in the specimens increase remarkably with the increase of the heating-rate, which corresponds to the reduction of the failure temperature. The comparisons between the metallographs of the material, subjected to the identical heating-rate but different pre-loaded stresses, σ=50, 100 and 150 MPa (Fig.5−7), show that there are more microdefects in the material at σ=100 and 150 MPa compared with those in the material at σ=50 MPa. It can be concluded that the microdefects in the material increase with the increase of the pre-load stress, which corresponds to the reduction of the failure temperature.

The changes of the microstructures and the mechanical properties of the pre-loaded material at the high heating-rates can be attributed to the local thermal inconsistency[14−15] in the material, which may increase the local residual stress and, in turn, expedite the nucleation, growth and coalescence of microvoids or other microdefects in the material. Severe thermal inconsistency at high heating-rate can result in very high

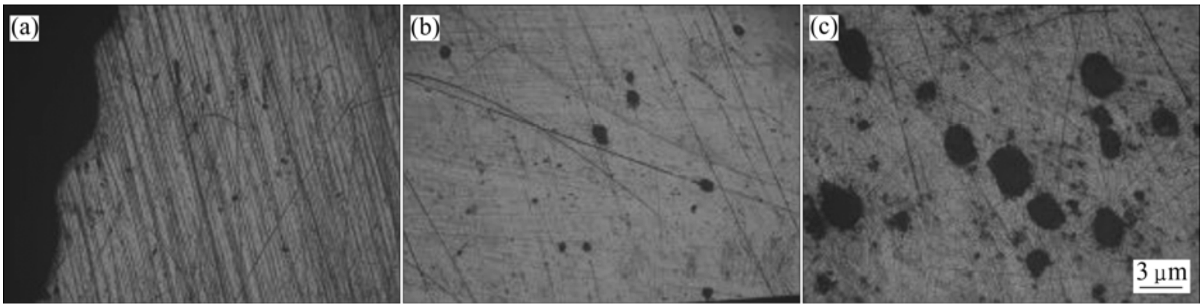

Fig.5 Metallographs at pre-stress of σ=50 MPa and different heating rates: (a) 100 ˚C/s; (b) 300 ˚C/s; (c) 500 ˚C/s

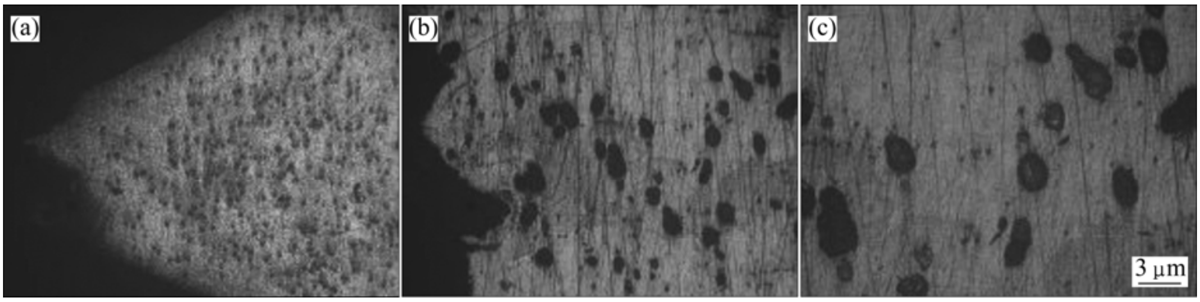

Fig.6 Metallographs at pre-stress σ=100 MPa and different heating rates: (a) 100 ˚C/s; (b) 300 ˚C/s; (c) 500 ˚C/s

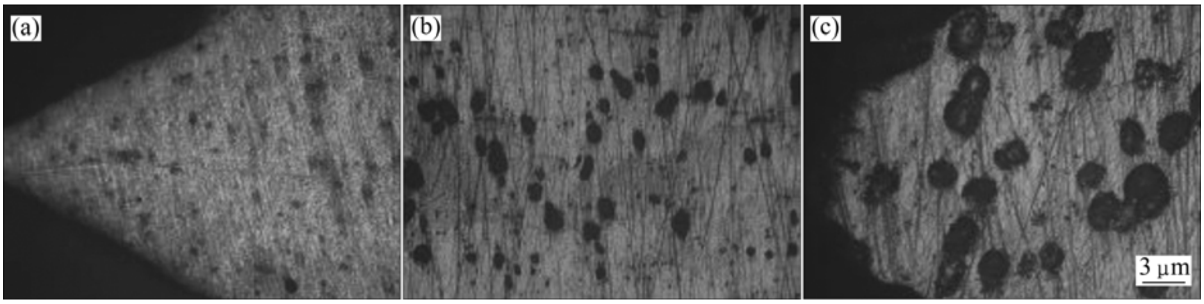

Fig.7 Metallographs at pre-stress σ=150 MPa and different heating rates: (a) 100 ˚C/s; (b) 300 ˚C/s; (c) 500 ˚C/s

local temperature, high local residual stress and induce microvoids or microcracks, which may markedly degrade the mechanical properties of the material and make the material fail even at a low level of pre-loaded stress.

4 Conclusions

1) The increases of pre-load stress decrease the failure temperature of the material.

2) The increases of heating-rate also decrease the failure temperature of the material.

3) The high heating-rate may cause stronger local thermal inconsistency, which will remarkably increase microvoids in the material and degrade the macroscopic mechanical properties of the material.

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