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Flow stress and softening behavior of wrought magnesium alloy AZ31B at elevated temperature①

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Abstract: The flow stress and softening behavior of AZ31B magnesium alloy in hot compression were investigated. The relationship of flow stress, temperature and strain rate was appropriately described with the exponential form of Zener-Hollemen parameter during steady state deformation of alloy at 573 - 723 K, 0.01 - 5s^{-1}. Dynamic recrystallization is the softening mechanism of AZ31B in hot compression. The flow curves of alloy have almost no peak value at 723 K and lower strain rate, presenting feature of geometric dynamic recrystallization.

Key words: magnesium alloy; compression; flow stress; dynamic recrystallization

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1 INTRODUCTION

The wrought magnesium alloys have excellent specific strength and stiffness, machinability, damp capacity, dimensional stability, low melting costs and are, hence, very attractive in such applications as automobile, aviation, electronic and communication industry[1-6].

Investigations on the flow stress and softening behavior of magnesium alloys at higher forming temperature and strain rate have been an important subject in wrought magnesium alloys forming[7-10]. In this paper the flow stress and softening behavior of AZ31B deformation magnesium alloy by compression at high strain rate and elevated temperature were studied, serving as the theoretical base for working out the plastic manufacturing parameters of magnesium alloy.

2 EXPERIMENTAL

The designation of the magnesium alloy used in this experiment was AZ31B. After being smelted in the crucible, the alloy was molded into bars with diameter of 18 mm. For homogenization, the bars were kept at 673 K for 12 h, then machined into specimens of d10 mm × 15 mm for compression.

High temperature compression experiment was conducted on the Gleeble-1500D hot simulator. Tantalum pieces were placed between the both ends of the specimen and the pressure heads to ensure a uniform temperature during heating and less friction during compression. The temperature was 573, 623, 673, 723 K, with heating rate of 2 K/s. Specimens were kept at fixed temperature for 5 min. Strain rates ($\dot{\varepsilon}$) were 0.01, 0.1, 1 and 5 s^{-1}, respectively.

3 EXPERIMENT RESULTS

Fig. 1 shows the true stress (σ)—strain (ε) curves of AZ31B alloy compressed at varied temperature and strain rate. As can be seen from Fig. 1, the flow stress in compression of AZ31B magnesium alloy generally increases drastically at first with the raising of true strain, followed by declination after reaching a certain peak value, finally tends to remain basically stable after the true strain gets to a certain value. The value gap between each peak stress and its correspondent flow stress narrows down as the temperature increases. The peak stress is almost the same as the flow stress in stable stage at 723 K, that is, no peak stress ever occurs. The peak value increases with the raising of strain rate at a fixed temperature, and decreases with the increase of temperature when the strain rate is fixed. It can also be seen in Fig. 1 that the true strain upon entering the stage of stable deformation increases with the enhancement of strain rate and decreasing of temperature.

4 ANALYSIS AND DISCUSSION

4.1 Effect of strain rate on flow stress

The strain rate is decided by thermal agitation when metal or alloy is under hot working. The effects of temperature and strain rate on forming can be integrated with the employment of Zener-

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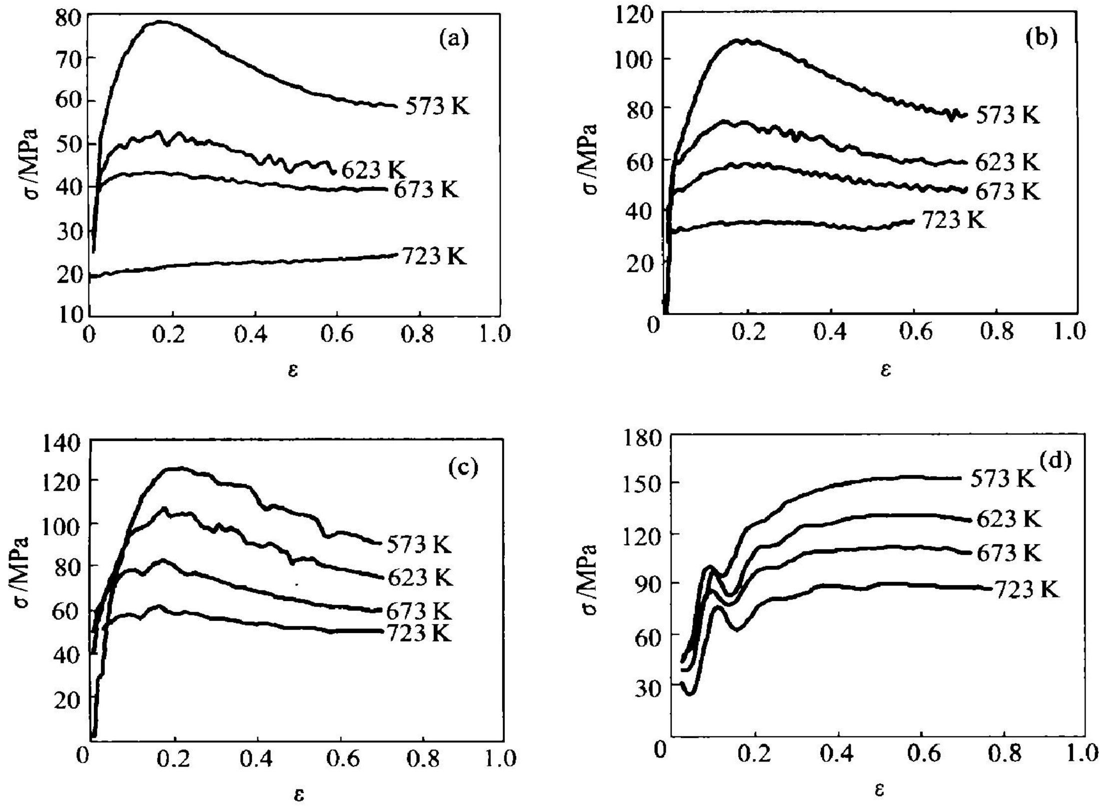

Fig. 1 Compressive true stress—strain curves for AZ31B magnesium alloy at different test temperatures and strain rates
(a) —0.01 s^{-1}; (b) —0.1 s^{-1}; (c) —1s^{-1}; (d) —5s^{-1}

Hollomon parameter[7]:

$$Z = \dot{\varepsilon}\exp(Q/RT) \tag{1}$$

where R is gas constant, Q is the deformation agitation energy.

Usually the relation among stress, strain rate and temperature can be written as

$$\dot{\varepsilon} = AF(\sigma)\exp(-Q/RT) \tag{2}$$

Namely

$$Z = AF(\sigma) \tag{3}$$

where A is constant independent of temperature, but only related to strain.

Fig. 2 displays the relation between strain rate and flow stress at various temperatures (with true strain of 0.23). It can be seen from Fig. 2 that flow stress is almost linear with the logarithm of strain rate at a fixed temperature. Linear regressions on the data reveal that flow stress is strongly linear with the logarithm of strain rate for the correlation coefficients being 0.966 - 0.992, and the slopes of the lines are nearly the same.

Study reveals that deformation agitation energy for AZ31B magnesium alloy is 135 kJ/mol[11]. Take the forming terms into Eqn. (1) to get the relation between parameter Z and flow stress, as shown in Fig. 3. The linear regression reveals that ln$Z$ is linear with flow stress and the correlation coefficient is 0.985, which indicates that the function of the flow stress for AZ31B magnesium alloy can be written as its exponential form. That is,

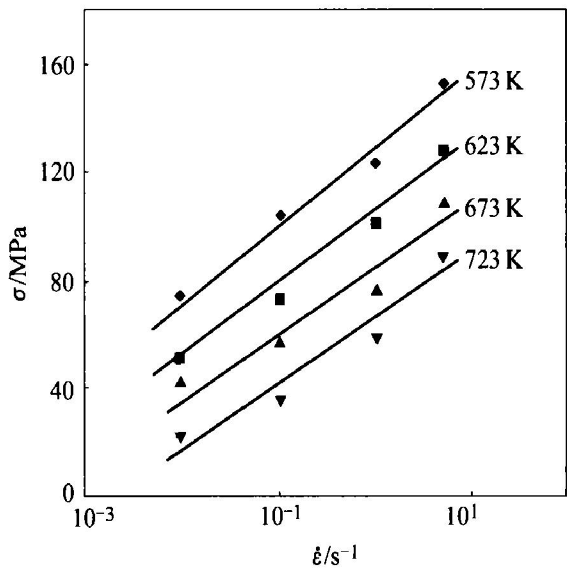

Fig. 2 True stress—true strain rate curves of AZ31B magnesium alloy at different high temperatures

$$F(\sigma) = \exp(\beta\sigma) \tag{4}$$

where β is constant independent of temperature, but only relevant to the strain.

Substitute Eqn. (4) into Eqn. (3) to obtain parameter Z written as the function of flow stress' exponent form:

$$Z = A\exp(\beta\sigma) \tag{5}$$

Using Z_0 to remove the dimension of Z and A, therefore Eqn. (5) can be simplified as

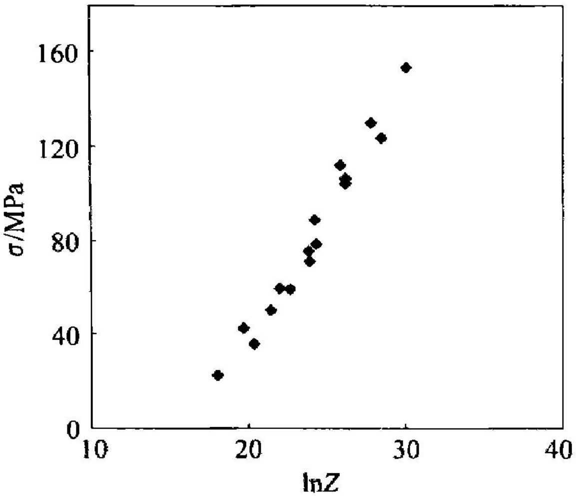

Fig. 3 Relationship between Zener-Hollomon parameter and stress of AZ31B at elevated temperature

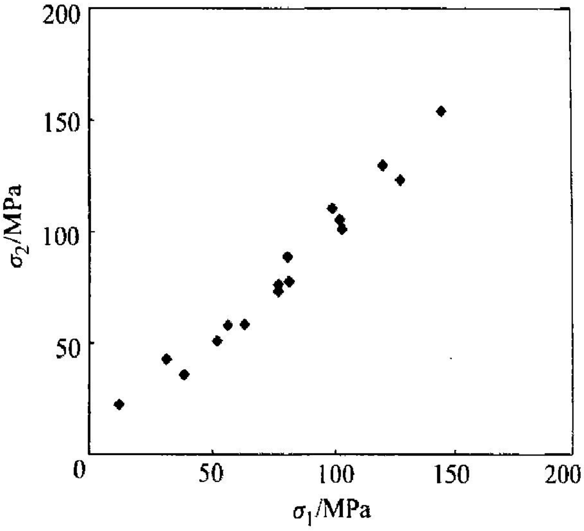

Fig. 4 Comparison between calculated(σ_2) and measured stress(σ_1)

$$\sigma = (1/\beta)\ln(Z/Z_0) - (1/\beta)\ln(A/Z_0) \quad (6)$$

Let coefficients $B = 1/\beta$, $C = -(1/\beta)\ln(A/Z_0)$, Eqn. (6) can be written as

$$\sigma = B\ln(Z/Z_0) + C \quad (7)$$

where B and C are constants independent of temperature. Let Z_0 to be $10^7 s^{-1}$ in this study.

Linear regression is made on the experimental data with Eqn. (7) according to the relation between flow stress and Zener-Hollomon parameter, with the regression coefficient B and C being 10.933 MPa and 5.967 MPa respectively. The model can be written as

$$\sigma/\text{MPa} = 10.933\ln(Z/Z_0) - 5.967 \quad (8)$$

Fig. 4 shows the relation between the experimental value of flow stress and the predictive value by Eqn. (8), from which it is clear that the predictive value matches the experimental value well. This indicates the exponential relation between the flow stress and strain rate of AZ31B under hot compression at high strain rate. The model can be used to describe the relation between the strain rate and flow stress of AZ31B at elevated temperature.

4.2 Effect of temperature on flow stress

As can be seen from stress—strain curves in Fig. 1, temperature has great effect on the flow stress of AZ31B. The exponential function is used to describe the relation between flow stress and parameter Z when the strain rate is fixed. From Eqns. (1) and (5) we can have

$$\sigma = \ln\dot{\varepsilon} - \ln A + \frac{Q}{R}T^{-1} \quad (9)$$

Let $D = \ln\dot{\varepsilon} - \ln A$, $G = Q/R$, Eqn. (9) can be written as

$$\sigma = GT^{-1} + D \quad (10)$$

where D is constant irrelevant to temperature, while G is constant relevant to strain and strain rate but not to temperature.

According to the experiment result, Fig. 5 shows the relation between temperature and flow stress. After regression analysis is made about the experimental data, it has been found that flow stress is linear with the reciprocal of temperature with the correlation coefficient of 0.986 ~ 0.999 when the strain rate is fixed. This means that Eqn. (10) describe well the relation between flow stress and temperature, and that the exponential form of Zener-Hollomon is capable of describing the flow stress of AZ31B deformed at high temperature.

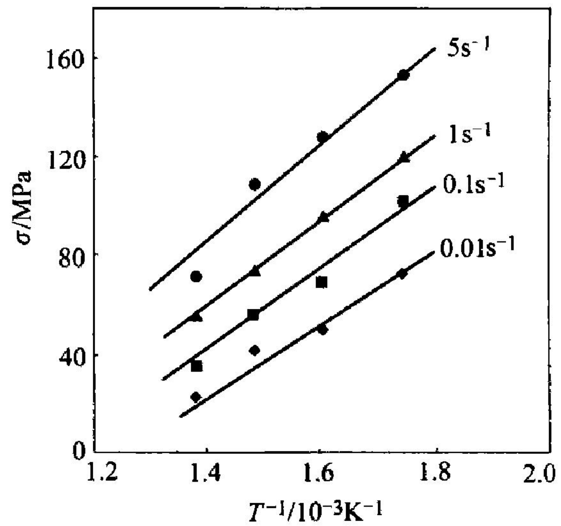

Fig. 5 Relationship between flow stress and temperature at various test strain rates

From the analysis above, it is evident that the flow stress of AZ31B is, to a large extent, decided by the deformation temperature and strain rate at elevated temperature and fast deformation, and that the exponential form of Zener-Hollomon parameter can be used to describe its flow stress at elevated temperature deformation.

4.3 Analysis of softening behavior

The dynamic recrystallization of AZ31B in hot compression at investigated conditions is shown in Fig. 1. The finer dynamic recrystallized grain after deformation is shown in Fig. 6.

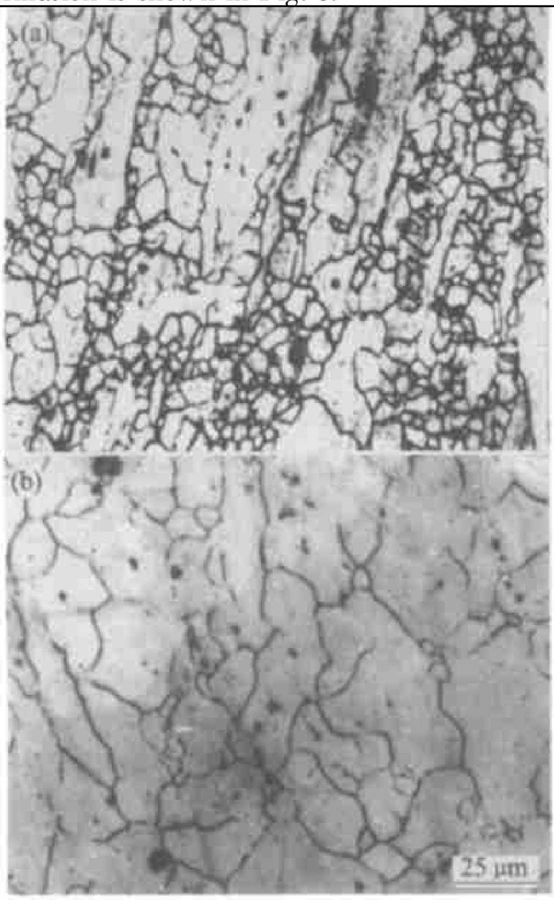

Fig. 6 Microstructures of AZ31B at investigated deformation conditions
(a) —573 K, $1s^{-1}$; (b) —723 K, $0.01s^{-1}$

The value gap between peak stress and flow stress and its correspondent strain increase as strain rate increases below 673 K. There are some reasons to explain this point. Because deformation of material keeps pace with dynamic recrystallization at hot compression, new recrystallized grains are deformed during growing, the interior energy of material varies from zero to critical value, and the dislocation density of each sub-grain is different.

The peak stress is almost equal to the flow stress in stable stage at 723 K and lower strain rate. In this deformation conditions, the dynamic recrystallization don't re-nucleate, while large-angle grain boundaries develop with increase of deformation degree and orientation between sub-grains, so presenting features of geometric dynamic recrystallization[12].

5 CONCLUSIONS

1) The flow stress in fast deformation of AZ31B at elevated temperature is strongly related to deformation temperature and strain rate. The relationship of flow stress, deformation temperature and strain rate of AZ31B at higher temperature and strain rate can be described with the exponential form of Zener-Hollomon parameter.

2) The main softening mechanism of AZ31B at investigated conditions is dynamic recrystallization. The curves of flow stress have almost no peak value at higher temperature and lower strain rate, presenting feature of geometric dynamic recrystallization.

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