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Hot compression deformation behavior of MB26 magnesium alloy

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Abstract: The flow stress features of MB26 magnesium alloy were studied by isothermal compression at 300−450 ℃ and strain rate of 0.001−1 s^{-1} with Gleeble 1500 thermal simulator. In addition, the deformation activation energy Q was calculated. The results show that the strain rate and deformation temperature have obvious effect on the true stress. The peak value of flow stress becomes larger with increasing strain rate at the same temperature, and gets smaller with the increasing deformation temperature at the same strain rate. The alloy shows partial dynamic recrystallization. The flow stress of MB26 magnesium alloy during high temperature deformation can be represented by Zener-Hollomon parameter including the Arrhemius term. The temperature range of 350−400 ℃ is suggested for hot-forming of this alloy.

Key words: MB26 magnesium alloy; hot compression deformation; flow stress

1 Introduction

Magnesium alloys, whose densities are approximately 1.8 g/cm^3, have been one of the lightest metal structural materials in practical application. As these alloys have superior properties of amortization and radiation resistance, they have potential great application in the areas of aerospace[1−3]. However, magnesium alloys, with hexagonal close-packed (HCP) structure and few slip system, are difficult to process by plastic forming at room temperature. So, these magnesium alloys were usually produced by hot-forming. During the hot-forming process, continuous and discontinuous dynamic recrystallization occurs in the microstructure. Degree and microstructure of dynamic recrystallization determine the properties of alloys by hot-forming, and have great effects on the properties and structures of alloys during subsequent processing. Consequently, it is significant to study the alloy deformation features. Hot deformation behaviors of many magnesium alloys, i.e., AZ31, AZ91, ZK60, et al, have been extensively investigated. As a new type alloy developed in our country, MB26 is obtained by coupling Y hybrid thulium into MB15 and has more excellent mechanical and corrosion resistance properties. However, there has yet almost not any reports regarding the hot deformation behavior of MB26.

In this paper, the flow stress features of MB26 magnesium alloy were investigated by isothermal compression at 300−450 ℃ and a strain rate of 0.001−1 s^{-1} with Gleeble 1500 simulated machine. This research may lay the foundation for selecting hot-forming conditions of the alloy.

2 Experimental

The MB26 magnesium alloy was used for this study, whose chemical composition is listed in Table 1. Compressive specimens with a diameter of 10 mm and a height of 15 mm were used. Isothermal compression deformation was carried out at 300−450 ℃ and strain rate of 0.001−1 s^{-1} with Gleeble 1500 thermal simulator. A graphite type lubricant was used to reduce the friction between the specimen and the loading platen. All the specimens were compressed to a true strain of 0.7. The temperature ascended at the rate of 2 ℃/s, and the holding time was 3 min. The true stress—strain curves were drawn immediately by computer with signals received by a strain-sensor during hot compression.

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Table 1 Chemical composition of MB26 magnesium alloy (mass fraction, %)

Zn	Zr	Mn	Al	Fe	Si	Cu	Y	Mg
6.33	0.79	0.01	0.004	0.003	0.002	0.002	0.93	Bal.

3 Results and discussion

3.1 curves of true stress—strain

Fig.1 shows the true stress—strain curves of the specimens, which were compressed at various strain rates of 0.001, 0.01, 0.1 and 1 s^{-1} and at temperature of 300, 350, 400 and 450 ℃.

The steady-state flow characteristics of the MB26 alloy during the hot-deformation are shown in Fig.1. At all the deformation temperatures and strain rates, the flow stress increases with the strain and tends to be constant after a peak value, which indicates that the alloy occurs dynamic recrystallization during hot-forming. Before the flow stress reaching the peak value, the work hardening is dominant factor. Thus the alloy only shows partial dynamic recrystallization. With increasing the strain, the dislocation density increases and dynamic recrystallization strengthens, which induce the degree of emollescence to enhance gradually. When the degree of emollescence is higher than that of work hardening, the flow stress begins to descend. With deformation continues, work hardening will reach equilibrium with emollescence, and the flow stress value will gradually trend to steady.

Fig.1 also shows that the peak value of the flow stress and its corresponding strain both descend with the increase of the temperature at the same strain rate. As a result of the critical shear stress of slip system reducing, the resistance to deformation of this alloy debases with increasing deformation temperature. Furthermore, the temperature is higher, then driving force of the atom diffusion and the dislocation gliding and climbing is greater, which will promote the occurring of dynamic recrystallization. At the same temperature, the flow stress and its peak value corresponding strain increases with increasing strain rate, which indicates that it is difficult to occur dynamic recrystallization with increasing strain rate.

3.2 Flow stress equation of hot deformation

During the hot deformation process, the flow stress, σ, of the materials with different conditions of strain and steady-state, strongly depends on the deformation temperature, T, and the strain rate, ε. The investigation for different hot-process data demonstrates that the mathematic relations between σ and ε include three cases as follow[9−11]:

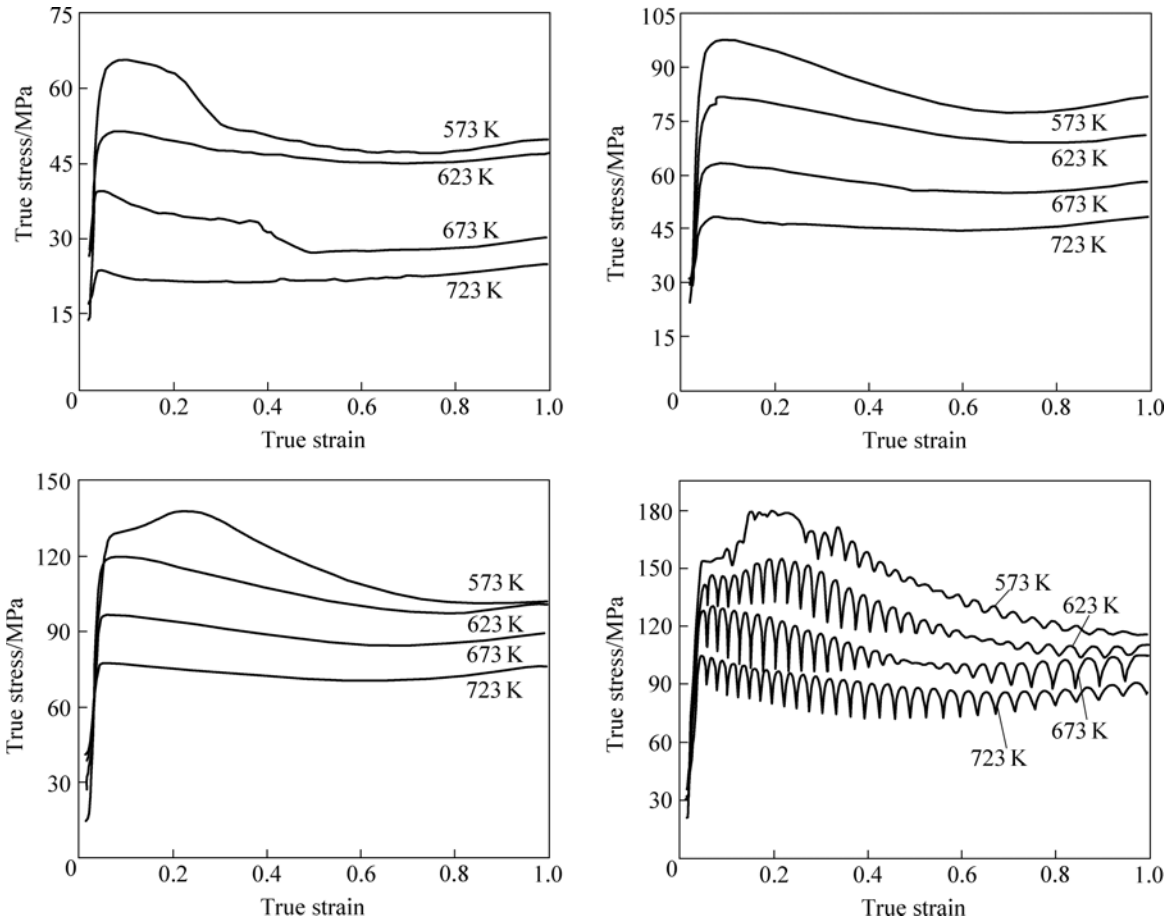

Fig.1 True stress—strain curves of MB26 magnesium alloy in hot compression at different temperatures

1) For the low strain stress,

$$\varepsilon = A_1 \sigma^{n_1} \tag{1}$$

2) For the high strain stress,

$$\varepsilon = A_2 \exp(\beta\sigma) \tag{2}$$

3) in the whole scale,

$$\varepsilon = A[\sinh(\alpha\sigma)]^n \exp[-Q/(RT)] \tag{3}$$

where A_1, A_2, A, n_1, n, α and β are parameters which have no relations with temperature. A is the structure factor (s^{-1}), n is the stress constant, α indicates the level of the stress (MPa^{-1}), R is the gas constant; T is the deformation temperature, Q is the active energy of the deformation. The parameters of α, β and n have the relations as $\alpha = \beta/n$. σ denotes the peak stress, the flow stress in the steady-state and the relative strain stress in the determined strain parameter.

Eqn.(3), which was deduced by Sellars and Tegart in 1966, is one of Arrehenius relations including the active energy of the deformation, Q, and the amended double arch sine for the temperature. It can be used to characterize the hot deformation behavior in the steady-state. Many works demonstrate that Eqn.(3) can characterize the general deformation behavior in hot-process appropriately. Moreover, it can also be used to estimate the active energy, Q, of different metals or alloy.

In 1944, Zener and Hollomon prompt and prove that the relation between the strain rate and the temperature can be described by a parameter, Z, which can be defined as follows

$$Z = \varepsilon \exp[Q/(RT)] \tag{4}$$

where Z is the Zener-Hollomon parameter and is the deformation rate factor on the temperature compensation. The active energy, Q, which reflects the degree for the hot deformation of the materials, is also the important dynamic parameter during the hot-deformation process. Its value usually equals to the active enthalpy, ΔH. Z and σ obey the relation as follows:

$$Z = A[\sinh(\alpha\sigma)]^n \tag{5}$$

In the investigation on the hot-deformation behavior of the materials, it is important to learn the change rule of the flow stress which has a relation with strain rate and the temperature. Eqn.(5) can be changed into:

$$\sinh(\alpha\sigma) = (Z/A)^{1/n} \tag{6}$$

According to the definition of the double arch sine, we can find

$$\sinh^{-1}(\alpha\sigma) = \ln[\alpha\sigma + ((\alpha\sigma)+1)^{1/2}] \tag{7}$$

Thus, the flow stress can be characterized by the function of strain rate and the temperature, and can also be characterized by the function of Zener-Hollomon parameter, Z.

$$\sigma = \frac{1}{\alpha \ln\left\{(Z/A)^{1/n} + \left[(Z/A)^{2/n} + 1\right]^{1/2}\right\}} \tag{8}$$

Practically, if the materials constants, i.e., A, Q, n, α, et al, can be known, the flow stress of the material with arbitrary deformation conditions can be obtained. Eqn.(8) has been used in the investigation of different hot-process technologies such as extrusion, rolling, compression, rotation and so on. Next, the materials constants, i.e., A, Q, n, α et al, are calculated firstly.

Both two sides of Eqns.(1) and (2) are taken the logarithm calculation, then

$$\ln\varepsilon = \ln A_1 + n_1 \ln\sigma \tag{9}$$

$$\ln\varepsilon = \ln A_2 + \beta\sigma \tag{10}$$

On the basis of Eqns.(9) and (10), the flow stress is defined as the peak stress. As Fig.2, the figure can be drawn using lnσ—lnε and σ—lnε as x and y axis, respectively. Then, the data are linearly fitted by the software. It is known from Eqns.(9) and (10) that n_1 can be defined as the average slopes of the five lines in Fig.2(a), i.e., n_1=5.871 455, β = 0.069 117 5 can be obtained through calculating the average slopes of the four lines, from 300 to 450 ℃, in Fig.2(b). Then, α can be calculated as

$$\alpha = \beta/n_1 = 0.01177$$

If both two sides of Eqn.(3) are taken logarithm calculation and the active energy of deformation is assumed to having no relation with the temperature, then

$$\ln\varepsilon = \ln A - Q/(RT) + n\ln[\sinh(\alpha\sigma)] = A' + n\ln[\sinh(\alpha\sigma)] \tag{11}$$

The peak deformation flow stresses and strain rates of MB26 alloy with deferent deformation temperatures are substituted into Eqn.(11). The figure is drawn using lnε and ln[sinh($\alpha\sigma$)] as x and y axis, respectively. Then, the data are linearly fitted by the software, Origin. It can be seen from Fig.3 that the logarithmic flow stress of high temperature deformation and the logarithmic strain rate obey the linear relation excellently. Thus, it can be think that the relation between the strain stress and the strain rate of MB26 alloy in the high temperature deformation appears a form of double arch sine. In the other word, the function of double arch sine can be used to describe the relation between the strain stress and the strain rate on the whole stress level, which is the theoretical evidence that the stain rate can be used to

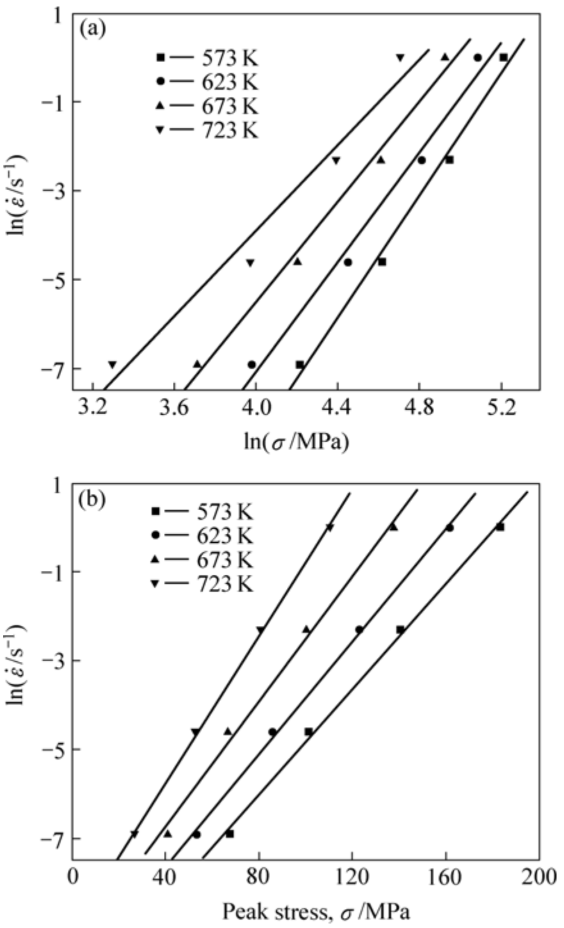

Fig.2 Relationships between peak stress and strain rate

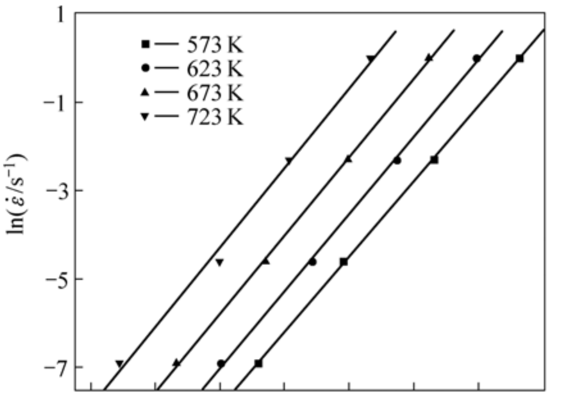

Fig.3 Relationships between peak stress and strain rate

tune the level of the stress in the hot-process.

Submitting Eqn.(4) into Eqn.(5) and taking the logarithmic calculation for the both two sides, the follow equation can be obtained,

$$\ln[\sinh(\alpha\sigma)] = A_3 + B\times 1\,000/T \quad (12)$$

The peak stresses under different conditions are substituted into Eqn.(12) and 1 000/T is plotted against

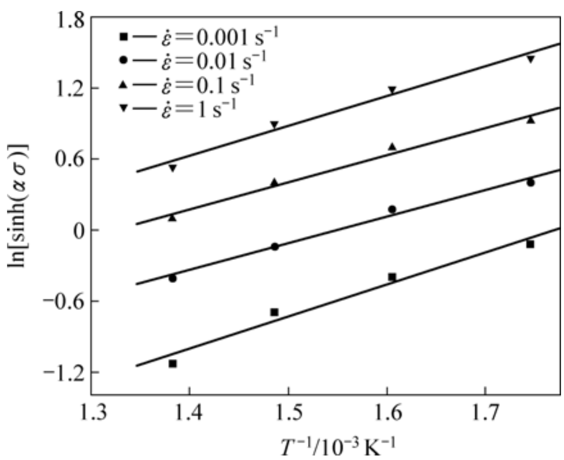

Fig.4 Relationships between peak stress and temperature

ln[sinh($\alpha\sigma$)]. Then the data are linearly regressed. From Fig.4, it can be found that σ and T obey the linear relation as in Eqn.(12), which demonstrates that the relationship between σ and T of MB26 alloy during high temperature deformation is one of the Arrhenius relation. Thus, the parameter Z including the Arrhenius item can be used to characterize the flow stress behavior of MB26 alloy in the high temperature. At the same time, this relationship illustrates that the hot-compression deformation of MB26 alloy is controlled by active energy.

The partial differential equation of Eqn.(3) is

$$Q = R\{\partial \ln\varepsilon/\partial \ln[\sinh(\alpha\sigma)]\}_T\ \{\ln[\sinh(\alpha\sigma)]/\partial(1/T)\}_\varepsilon \quad (13)$$

The two items in the right side of Eq.(13) indicate the slopes of ln[sinh($\alpha\sigma$)]—lnε in the certain temperature and the slopes of (1/T)—ln[sinh($\alpha\sigma$)] in the certain strain rate. Substituting the slopes, 4.378 56 and 2.445 49, of the lines in Figs.3 and 4 into Eqn.(13), the active energy, Q, can be calculated as 89.024 kJ/mol.

Both sides of Eqn.(5) is done the logarithmic calculation, then

$$\ln Z = \ln A + n\ln[\sinh(\alpha\sigma)] \quad (14)$$

Z can be calculated by substituting Q and the deformation condition into Eqn.(4). The figure is drawn using ln[sinh($\alpha\sigma$)] and ln$Z$ and the data are linealy regressed. From Eqn.(14), the slopes in Fig.5 is really the stress index, n, and the intercept is really ln$A$. From Fig.5, it can be known that n = 4.38 and $A = 1.86\times10^5$ s^{-1}.

Substituting the values of different materials parameters into Eqn.(3), the flow stress equation of MB26 alloy during hot-compression can be obtained as follows:

$$\varepsilon = 1.86\times10^5 \ln[\sinh(0.011\,77\sigma)]^{4.38}\exp[89.024/(RT)]$$

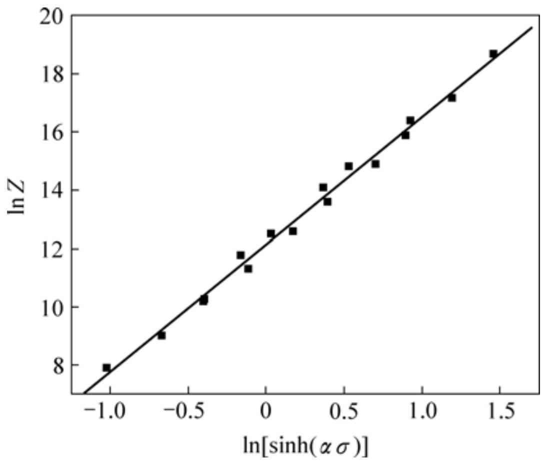

Fig.5 Relationship between flow stress and Zener-Hollomon parameter

where Z can be described as

$$Z=\varepsilon\exp[89.024/(RT)]$$

The equation of flow stress can also be described with Z parameter as follows:

$$\sigma=84.96\ln\left\{[Z/(1.86\times10^5)]^{1/4.38}+[Z/(1.86\times10^5)]^{2/4.38}+1\right\}^{1/2}$$

4 Conclusions

1) Strain rate and deformation temperature have obvious effect on the true stress. The peak value of flow stress becomes larger with increasing strain rate at the same temperature, and gets smaller with increasing deformation temperature at the same strain rate.

2) The alloy shows partial dynamic recrystallization. The temperature range of 350−400 ℃ is suggested for hot-forming of this alloy.

3) The flow stress of MB26 magnesium alloy during high temperature deformation can be represented by Zener-Hollomon parameter including the Arrhemius term. The parameters of A, α and n can be calculated as $1.86\times10^5\ s^{-1}$, 0.011 77 and 4.38. The active energy of the deformation, Q can be calculated as 89.024 kJ/mol.

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