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ARTICLE

Hot Compression Behavior of Mg-5Y-0.5Ce-0.5Zr Alloy

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Abstract: The hot deformation behavior of Mg-5Y-0.5Ce-0.5Zr magnesium alloy was studied by hot compression tests at deformation temperatures from 300 to 450 °C and strain rates from 0.01 to 1 s^{-1}. The results show that the flow stress of the alloy is changed with deformation temperature and strain rate during the hot compression deformation. The flow stress of the alloy decreases with increasing the deformation temperature at the same strain rate, and decreases with decreasing the strain rate at the same deformation temperature. The constitutive equation for hot compression flow stress of the alloy is established in a hyperbolic-sine form. The hot deformation activation energy Q of the alloy is 253 kJ/mol.

Key words: magnesium alloy; hot compression; flow stress; activation energy

Magnesium alloys have the lowest density among metal structural materials in engineering applications, and have broad application prospects in aerospace, weapon equipment, automobile industry, electronic products and other fields[1-3]. However, magnesium alloys are in hexagonal close-packed structure, and the number of activable slip system at room temperature and low temperature is less than that of aluminium alloys. It results in poor plasticity and formability of magnesium alloys, and the development and application of wrought magnesium alloys are limited[4-6]. Usually, the deformation ability of materials can be improved by hot working, and the constitutive equation is used to describe the basic information during deformation. Therefore, it is of great theoretical and practical value to study the deformation behavior and deformation law of magnesium alloys during hot working. And it is very important to establish constitutive equations to describe the relationship among deformation parameters of magnesium alloys[7-10].

It has been an effective method to strengthen the mechanical properties of magnesium alloys by adding appropriate rare earth elements. Among the available rare earth elements, Y (yttrium) has been generally considered to have the most significant effect on improving the heat resistance of magnesium alloys. Therefore, more and more research has been reported on the application of Y to enhance the mechanical properties of magnesium alloys[11-14]. However, there have been few reports on the deformation properties of Mg-Y system heat-resistant magnesium alloys. In this work, Mg-5Y-0.5Ce-0.5Zr magnesium alloy was taken as the research object, and hot compression tests were carried out under different deformation conditions to study its flow stress and microstructure evolution. The hot deformation activation energy was calculated through data processing, and then the constitutive equation was established. It was hoped to provide theoretical reference and experimental basis for the optimization of hot-working process of heat-resistant magnesium alloys.

1 Experiment

The experimental material was as-cast magnesium alloy, whose chemical composition was Mg-5Y-0.5Ce-0.5Zr (mass fraction, %). Alloy smelting was carried out in an induction furnace, using a corundum crucible to load raw materials, including pure magnesium and Mg-Y, Mg-Ce, Mg-Zr master alloys. After the melting of raw materials, the alloy ingot was obtained by heating up the alloy liquid to 750 °C, holding for a certain time and then pouring in a preheated casting mould.

The ingot was sliced into thin pieces and machined into

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cylindrical specimens with diameter of 10 mm and height of 15 mm. The hot compression tests were carried out on Gleeble 1500D thermal simulator. The deformation temperatures T were 300, 350, 400 and 450 °C, namely 573, 623, 673 and 723 K. The strain rates were 0.01, 0.1 and 1 s^{-1}. The maximum strain was 0.7. After hot compression deformation, the specimens were cut along the longitudinal section to prepare metallographic specimens, and the microstructure was observed by optical microscope after hot deformation. Before hot deformation, the microstructure and phases of the alloy were examined by optical microscope and XRD, respectively.

2 Results and Discussion

2.1 Flow stress

The true stress-true strain curves of Mg-5Y-0.5Ce-0.5Zr magnesium alloy during hot compression are shown in Fig. 1. It can be seen that the true stress increases rapidly with the increase of true strain because of work hardening in the initial plastic deformation stage. And a peak value of flow stress appears when the balance is reached between dynamic recrystallization softening and work hardening. Then, there is a gradual decrease in the flow stress. It shows that the alloy has obvious dynamic recrystallization characteristics.

It can also be seen from Fig. 1 that deformation temperature and strain rate have a great influence on the flow stress of the alloy. When the deformation temperature is constant, the true stress decreases with the decrease of strain rate. When the strain rate remains unchanged, the true stress decreases with the increase of deformation temperature.

2.2 Microstructure evolution

Fig.2 shows the microstructure and XRD pattern of Mg-5Y-0.5Ce-0.5Zr alloy before hot compression. It can be seen that the microstructure of the as-cast alloy consists of white matrix (α-Mg) and black intermetallic compound phases (including $Mg_{24}Y_5$ and $Mg_{12}Ce$). The compound phases have a great effect on the hot compression deformation of the alloy. With the increase of deformation temperature, the hardness of these compound phases decreases, the strengthening effect on the alloy decreases, and the strength and hardness of the alloy decrease. Meanwhile, the plasticity of the alloy increases and the deformation ability improves. Therefore, the deformation resistance of the alloy decreases, resulting in the decrease of flow stress with the increase of deformation temperature.

When the strain rate is 0.01 s^{-1}, the microstructure of hot compressed Mg-5Y-0.5Ce-0.5Zr alloy is shown in Fig.3. After hot compression deformation at 300 °C, some deformed and flattened grains are observed in the alloy, and the orientation of the deformed microstructure is obvious, as shown in Fig.3a. After hot compression at 350 °C, the alloy still shows deformed grains in the microstructure, and the orientation of the deformed microstructure is more obvious, as shown in Fig.3b. From the true stress-true strain curve, it can be seen that the work hardening phenomenon is still obvious at this time, and the flow stress falls back, which may be due to the dynamic recovery in the alloy. When the deformation temperature reaches 400 °C, fine grains appear around the initial grains in the microstructure, and obvious recrystallization occurs. However, the deformed microstructure still amounts to a large proportion, as shown in Fig.3c. When the deformation temperature is up to 450 °C, some new equiaxed grains are observed in the microstructure after hot compression deformation, as shown in Fig.3d. Obvious recrystallization occurs in the alloy, so the flow stress is low.

2.3 Constitutive equation

In order to determine the relationship between flow stress σ, deformation temperature T and strain rate $\dot{\varepsilon}$, Sellars and

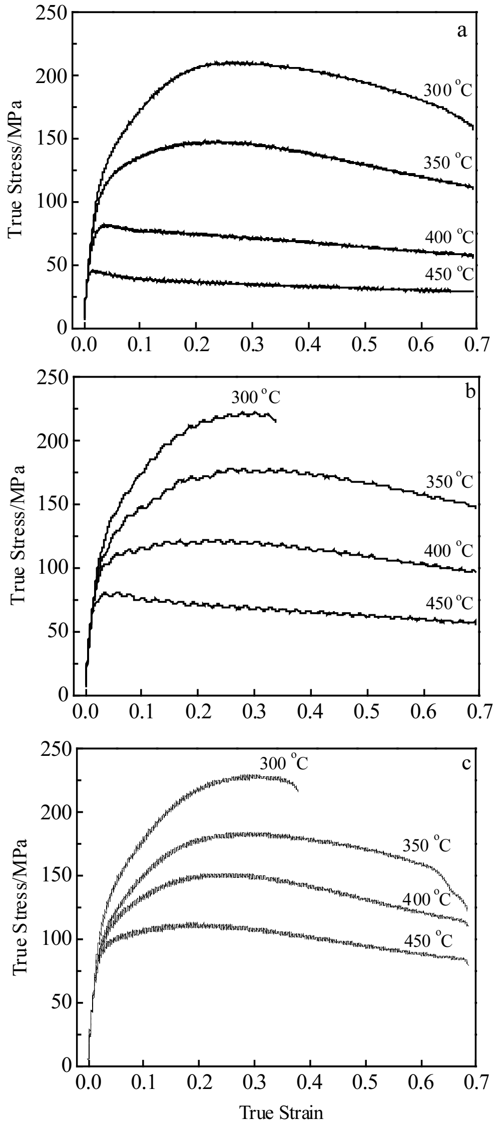

Fig.1 True stress-strain curves of Mg-5Y-0.5Ce-0.5Zr alloy at $\dot{\varepsilon}$=0.01 s^{-1} (a), $\dot{\varepsilon}$=0.1 s^{-1} (b), and $\dot{\varepsilon}$=1 s^{-1} (c)

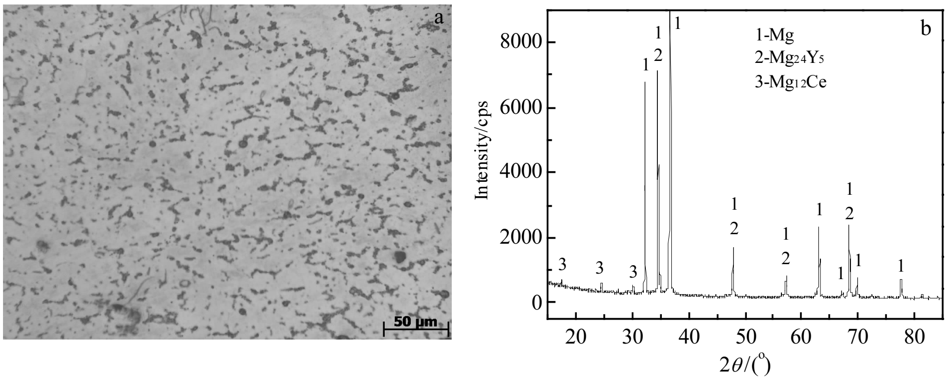

Fig.2 Microstructure (a) and XRD pattern (b) of Mg-5Y-0.5Ce-0.5Zr alloy before hot compression

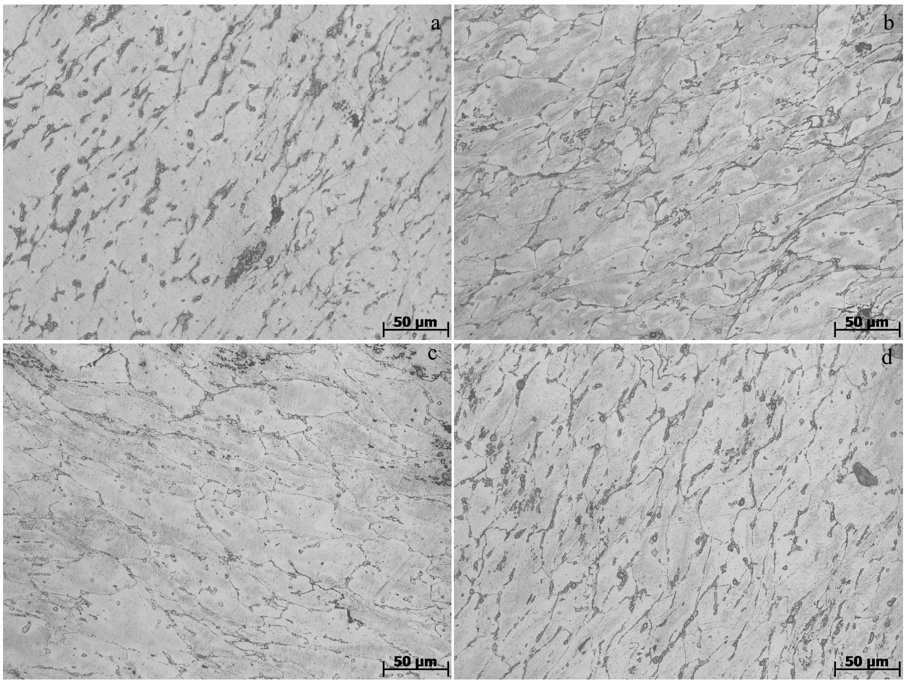

Fig.3 Microstructures of Mg-5Y-0.5Ce-0.5Zr alloy after hot compression at $\dot{\varepsilon}$=0.01 s^{-1} and 300 °C (a), 350 °C (b), 400 °C (c), and 450 °C (d)

Tegart proposed a modified Arrhenius equation in 1966, which can be expressed as a hyperbolic-sine form and contains hot deformation activation energy Q [15,16].

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp[-Q/(RT)] \tag{1}$$

where σ is the flow stress corresponding to a specified strain, in MPa; A, α, n are material constants independent of deformation temperature, A is the structural factor, α is the stress level parameter, and n is the stress index; R is the molar gas constant of 8.31 J/(mol·K); T is the absolute temperature, in K; Q is the hot deformation activation energy, in J/mol.

Constant α is the ratio of slope n' to β obtained through linear fitting from the relationship of $\ln\dot{\varepsilon}$ -lnσ and $\ln\dot{\varepsilon}$ -σ, i.e. $\alpha=\beta/n'$. In this experiment, according to the relationship between flow stress and strain rate (see Fig.4), α = 0.008 is obtained by fitting calculation.

Take the natural logarithms of both sides of Eq. (1) and assume that hot deformation activation energy is independent of deformation temperature, the following equation is obtained as

$$\ln\dot{\varepsilon} = \ln A + n\ln[\sinh(\alpha\sigma)] - Q/(RT) \tag{2}$$

According to the relationship of $\ln\dot{\varepsilon}$ -ln[sinh($\alpha\sigma$)] and ln[sinh($\alpha\sigma$)]-1/T, the slopes determined through linear fitting are recorded as n and b, respectively. It can be deduced from the differential form of both sides of Eq. (2) that

$$n = \frac{\partial \ln\dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]}\bigg|_T \tag{3}$$

$$b = \frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial(1/T)}\Big|_{\dot{\varepsilon}} \tag{4}$$

Based on the above results, the hot deformation activation energy can be expressed as

$$Q = R\frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]}\Big|_{T}\frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial(1/T)}\Big|_{\dot{\varepsilon}} = Rnb \tag{5}$$

From the relationship of flow stress with strain rate and temperature (see Fig. 5), the slopes are determined as n = 7.44, b = 4.10.

By substituting the values of R, n and b into Eq. (5), it can be obtained that the hot deformation activation energy for the experimental alloy is Q = 253 kJ/mol.

The hot deformation activation energy of Mg-5Y-0.5Ce-0.5Zr (253 kJ/mol) in this experiment is more than that of AZ31 alloy (196 kJ/mol) [6]. It can be attributed to the strengthening effect of alloying elements. The main strengthening phase in AZ31 alloy is $Mg_{17}Al_{12}$. Its melting point and hardness HV are very low (437 °C and 1830 MPa, respectively) [2]. And its strengthening effect on AZ31 alloy is limited. Therefore, the hardness of AZ31 alloy is low, and it is easy to compress and deform, so its hot deformation activation energy is low. In Mg-5Y-0.5Ce-0.5Zr alloy, some strengthening phases with high melting point and high hardness are formed. For example, the melting point and hardness HV of $Mg_{24}Y_5$ phase are 620 °C and 2180 MPa [2], respectively, which are higher than those of $Mg_{17}Al_{12}$ phase. Therefore, the hardness of Mg-5Y-0.5Ce-0.5Zr alloy is higher than that of AZ31 alloy. So it is more difficult for Mg-5Y-0.5Ce-0.5Zr alloy to compress and deform, and its hot deformation activation energy is higher than that of AZ31 alloy.

In order to facilitate the analysis, the effects of deformation temperature and strain rate can be combined into one parameter, Zener-Hollomom parameter, i.e. Z parameter:

$$Z = \dot{\varepsilon}\exp[Q/(RT)] = A[\sinh(\alpha\sigma)]^n \tag{6}$$

Taking the natural logarithm of both sides of Eq. (6) gives

$$\ln Z = \ln A + n\ln[\sinh(\alpha\sigma)] \tag{7}$$

Based on the relationship between flow stress and Z parameter (see Fig. 6), the result of linear regression analysis shows that $A = 3.78\times10^{18}$.

When substituting the above parameters into Eq. (1), the constitutive equation for hot compression flow stress of the experimental alloy can be expressed as:

$$\dot{\varepsilon} = 3.78\times10^{18}[\sinh(0.008\sigma)]^{7.44}\exp[-253000/(RT)] \tag{8}$$

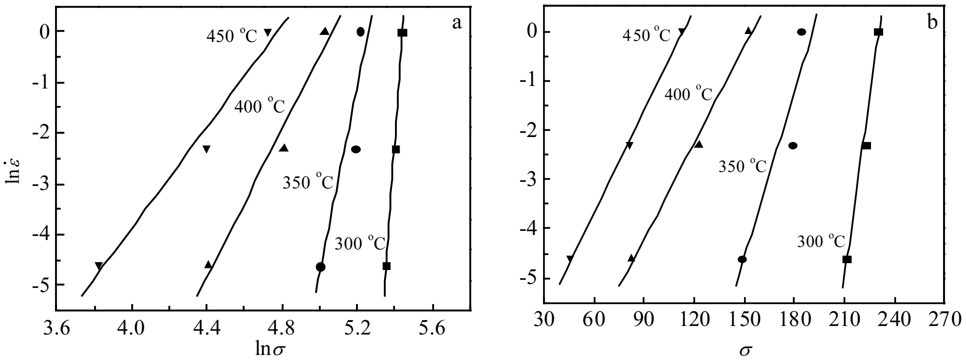

Fig.4 Relationship between flow stress and strain rate: (a) $\ln\dot{\varepsilon}$ -$\ln\sigma$ and (b) $\ln\dot{\varepsilon}$ -σ

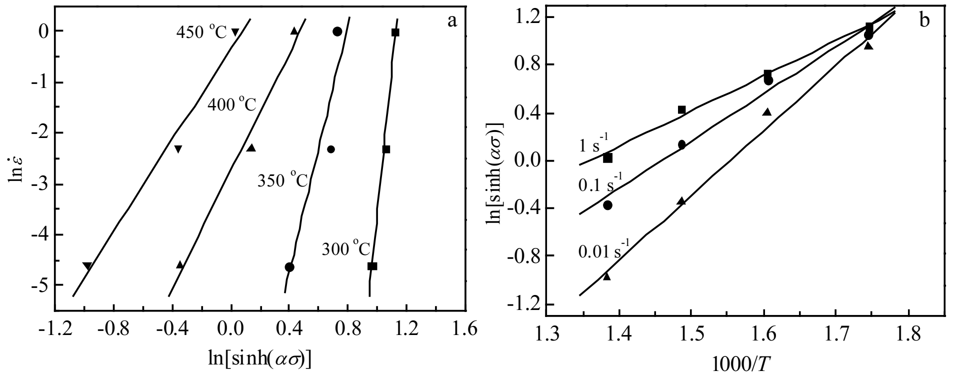

Fig.5 Relationship between flow stress and strain rate or temperature: (a) $\ln\dot{\varepsilon}$ -$\ln[\sinh(\alpha\sigma)]$ and (b) $\ln[\sinh(\alpha\sigma)]$-$1/T$

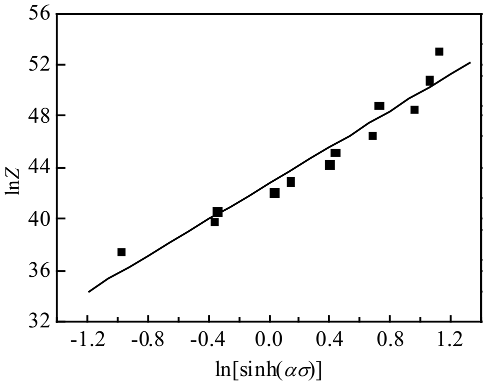

Fig.6 Relationship between flow stress and Z parameter

The obtained constitutive equation can provide some theoretical support for the analysis of actual production process of the alloy, and also provide some references for the optimization of hot working process of magnesium alloys.

3 Conclusions

1) During hot compression, the flow stress of Mg-5Y-0.5Ce-0.5Zr magnesium alloy is greatly affected by deformation temperature and strain rate. With the increase of deformation temperature and the decrease of strain rate, the flow stress decreases gradually.

2) Under the experimental conditions, the constitutive equation for hot compression flow stress of Mg-5Y-0.5Ce-0.5Zr magnesium alloy is established in a hyperbolic-sine form. The stress index n is 7.44, and the hot deformation activation energy Q is 253 kJ/mol.

References

1 Mordike B L, Ebert T. *Materials Science and Engineering A*[J], 2001, 302: 37

2 Chen Zhenhua. *Heat Resistant Magnesium Alloy*[M]. Beijing: Chemical Industry Press, 2007: 1 (in Chinese)

3 Zhang Q, Li Q A, Jing X T *et al*. *Journal of Rare Earths*[J], 2010, 28(S1): 375

4 Yan Yunqi, Zhang Tingjie, Deng Ju *et al*. *Rare Metal Materials and Engineering*[J], 2004, 33(6): 561 (in Chinese)

5 Ding Wenjiang. *Magnesium Alloy Science and Technology*[M]. Beijing: Science Press, 2007: 255 (in Chinese)

6 Xu Jing, Qi Wenjun, Huang Zhenghua *et al*. *Materials Research and Application*[J], 2013, 7(1): 21 (in Chinese)

7 Fang X Y, Yi D Q, Wang B *et al*. *Rare Metals*[J], 2008, 27(2): 121

8 Shi B L, Luo T J, Wang J *et al*. *Transactions of Nonferrous Metals Society of China*[J], 2013, 23(9): 2560

9 Xu J, Li C X, Zheng K H *et al*. *Rare Metal Materials and Engineering*[J], 2014, 43(11): 2572 (in Chinese)

10 Zhu L M, Li Q A, Zhang Q *et al*. *Materials*[J], 2018, 11(11): 2147

11 Zhao Y, Wang Q D, Gao Y. *Transactions of Nonferrous Metals Society of China*[J], 2012, 22(8): 1924

12 Li Q A, Zhang Q, Wang Y G *et al*. *China Foundry*[J], 2014, 11(1): 28

13 Zhang Q, Chen J, Li Q A. *Rare Metal Materials and Engineering*[J], 2018, 47(3): 799 (in Chinese)

14 Lü S Y, Xiao W L, Zheng R X *et al*. *Materials Science and Engineering A*[J], 2018, 732: 178

15 Sellars C M, Tegart W J M. *Acta Metallurgica*[J], 1966, 14(6): 1136

16 Poirier J P. Translated by Guan Delin. *The Plastic Deformation of Crystals at High Temperature*[M]. Dalian: Dalian University of Science and Technology Press, 1989: 25 (in Chinese)

Mg-5Y-0.5Ce-0.5Zr 合金的热压缩行为

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摘　要： 在变形温度为300～450 ℃、应变速率为0.01～1 s^{-1}的条件下进行热压缩试验，对Mg-5Y-0.5Ce-0.5Zr镁合金的热变形行为进行了研究。结果表明，在热压缩变形过程中，该合金的流变应力随着变形温度和应变速率的变化而变化。在同一应变速率下，流变应力随着变形温度的增高而降低；在同一变形温度下，流变应力随着应变速率的减小而减小。该合金热压缩流变应力的本构方程可采用双曲正弦形式构建，热变形激活能Q为253 kJ/mol。

关键词： 镁合金；热压缩；流变应力；激活能

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