P. HUO, F. L. ZHANG, X. Li

ISSN 0543-5846
METABK 63(1) 73-76 (2024)
UDC – UDK 669.721.5.296.546.65:620.173:620.16-539.374/513.6:536.45:621.72=111

HIGH TEMPERATURE PLASTIC DEFORMATION CONSTITUTIVE MODEL OF Mg-Zn-Zr-Y ALLOY

Received – Primljeno: 2023-05-08
Accepted – Prihvaćeno: 2023-08-25
Original Scientific Paper – Izvorni znanstveni rad

In order to accurately predict the flow stress of Mg-Zn-Zr-Y alloy at high temperature, the hot compression test of Mg-Zn-Zr-Y alloy was carried out on Gleeble-1500 thermal / mechanical simulator. The deformation temperature was 523 K, 573 K, 623 K, and the strain rate was 0,01 ~ 1 s^{-1}. By obtaining the true stress-strain curve, the strain compensation factor Z parameter was introduced into the Arrhenius equation to establish a more accurate strain coupling constitutive model. The results show that the theoretical value of the peak stress calculated by the constitutive model is in good agreement with the experimental results, and the average relative error is 5,67 %, which verifies the feasibility of the model.

Keywords: Mg-Zn-Zr-Y alloy; thermal compression test; stress-stain curves; temperature; constitutive mode

INTRODUCTION

The flow stress of high temperature deformation is the basic performance of materials. It is of great significance to formulate reasonable hot processing technology and study the theory of plastic deformation [1]. The constitutive equation of materials can describe the relationship between deformation temperature, reaction rate and flow stress. It is an effective method to study the plastic deformation of materials and one of the important factors affecting the accuracy of numerical simulation results [2].

Magnesium alloys are widely used in biomedical, automobile manufacturing, aerospace and defense military and other high-tech fields due to their advantages of low density, high specific strength and specific stiffness, good thermal and electrical conductivity, good damping and electromagnetic shielding effect and easy recovery [3]. In recent years, Mg-Zn-Zr magnesium alloy has become a typical representative of new high-strength wrought magnesium alloys. However, due to its poor plastic deformation ability and unstable high-temperature deformation, researchers at home and abroad have gradually added rare earth yttrium (Y) to Mg-Zn-Zr-Y alloy. A lot of research work has been carried out. Studies have shown that the addition of Y alloy to magnesium alloy can improve the high temperature performance of the alloy and improve the shortcomings of hot cracking of the alloy [4]. However, there is a lack of constitutive analysis of the rheological behavior of Mg-Zn-Zr-Y alloy at high temperature, and there is no accurate constitutive model, which limits the application of Mg-Zn-Zr-Y alloy in industry. Therefore, it is of great practical significance to construct a constitutive model that can accurately predict the flow stress.

In this paper, the high temperature compression deformation test of Mg-Zn-Zr-Y alloy was carried out by using Gleeble-1500 thermal / mechanical simulation testing machine under the conditions of deformation temperature of 523 ~ 623 K and strain rate of 0,01 ~ 1 s^{-1}. The true stress-strain curves of the alloy under different deformation conditions were obtained, and the Arrhenius constitutive equation of Mg-Zn-Zr-Y alloy under hot deformation conditions was established. The experimental data were compared with the model prediction data to verify the accuracy and feasibility of the constitutive model.

EXPERIMENTAL MATERIALS AND TECHNOLOGY

The test material is Mg-2,89Zn-0,48Zr-0,46Y (mass fraction / %) alloy. The alloy ingot is processed into a sample with a diameter of 10 mm and a height of 15 mm. The isothermal compression test was carried out on Gleeble-1500 thermal / mechanical simulator. The deformation temperature was 523 K, 573 K and 623 K, the strain rate was 0,01 s^{-1}, 0,1 s^{-1} and 1 s^{-1}, and the total compression strain was 0,7 (true strain). Before hot compression, graphite sheets were pasted at both ends of the sample to reduce friction. The sample was heated to a certain temperature at a heating rate of 5 K / s and held for 180 s to make the whole sample heated evenly, and then the isothermal hot compression test was carried out. In order to prevent the oxidation of the sample, argon protection is used during the compression pro-

P. Huo, F. L. Zhang (E-mail: huop@ncst.edu.cn), X. Li, College of Mechanical Engineering, North China University of Science and Technology, Hebei, Tangshan, China.

cess. When the isothermal compression reaches the set strain value, water quenching is immediately performed.

EXPERIMENTAL DATA AND CONSTITUTIVE MODEL ESTABLISHMENT

Figure 1 shows the true stress-strain curves of Mg-Zn-Zr-Y alloy at different temperatures and strain rates. It can be seen from the figure that at the same temperature, the flow stress increases rapidly with the increase of strain rate, which is the elastic deformation stage, and the strain hardening effect is remarkable. Then the flow stress reaches the peak after a slow increase, which is the continuous yield stage. Because the occurrence of dynamic recovery and recrystal-lizeation will offset part of the strain hardening effect, but the strain hardening is still dominant. Finally, the flow stress decreases very slowly and remains stable. The dynamic recrystallization is accelerated at this stage, so that the softening rate is greater than the hardening rate. When the crystallization softening and hardening reach a dynamic equilibrium, the macroscopic flow stress remains basically unchanged. It can be clearly seen from the figure that the higher the temperature, the lower the strain rate, the more prone to dynamic recrystallization. According to the description in the diagram, the flow stress of the alloy has entered the steady-state flow stage when the true strain ε is near 0,3, and reaches the maximum value. Therefore, the flow stress at $\varepsilon \approx 0,3$ is taken as the peak stress and used as the basic data for establishing the constitutive model.

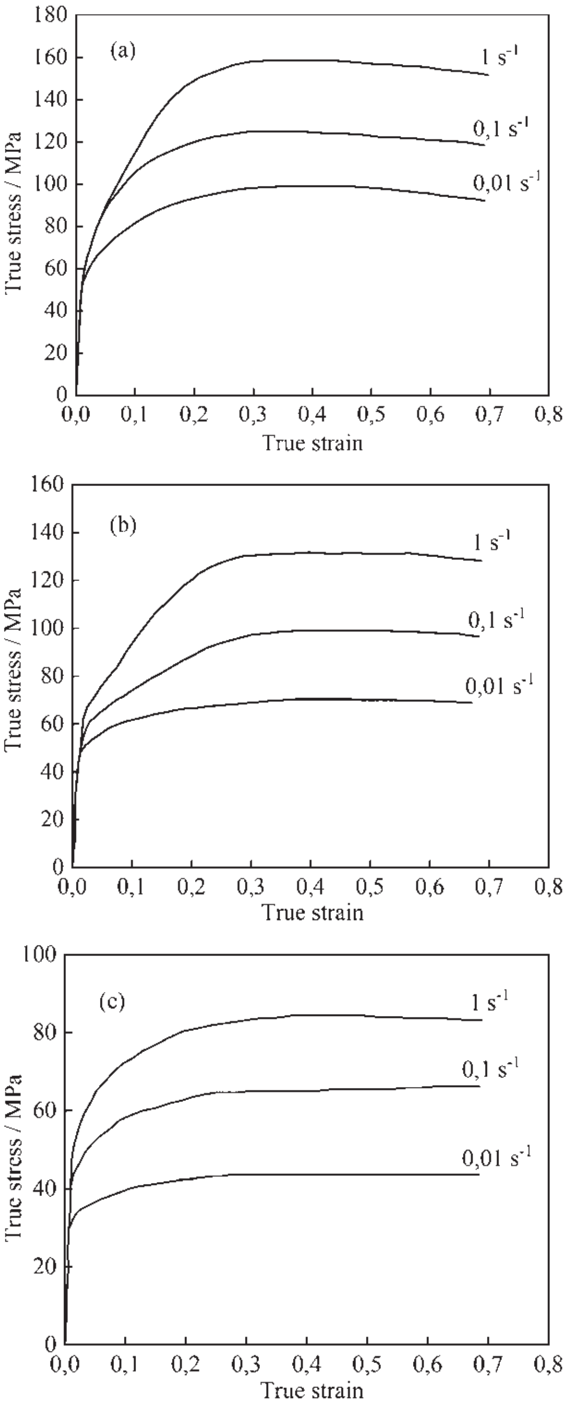

Figure 1 The true stress-strain curve of Mg-Zn-Zr-Y alloy at different temperature: (a) 523 K; (b) 573 K; (c) 623 K

The plastic deformation mechanism of Mg-Zn-Zr-Y alloy is complex and unstable due to its high temperature and strain rate sensitivity. Generally, the constitutive model is used to quantitatively describe the relationship between flow stress σ, strain rate $\dot{\varepsilon}$ and deformation temperature T. The influence of $\dot{\varepsilon}$ and T on the flow behavior can be revealed by the Zener-Hollomon exponential equation. Then, combined with the Arrhenius constitutive equation proposed by Sellars and Tegart, the relationship between Z parameter and $\dot{\varepsilon}$ during steady-state deformation is obtained:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \tag{1}$$

where: Z-strain compensation factor, R-molar gas constant / 8,314 $J \cdot mol^{-1} \cdot K^{-1}$; Q-thermal deformation activation energy / $J \cdot mol^{-1}$; T-absolute temperature / K; Under the condition of low strain rate, the relationship between Z parameter and σ satisfies the power function of equation (2). Under the condition of high strain rate, the relationship between Z parameter and σ usually satisfies the formula (3) exponential function. Under all strain rate conditions, the relationship between Z parameter and σ can be described by a unified hyperbolic sine relationship, which is shown in Equation (4):

$$Z = A_1 \sigma^{n'} \tag{2}$$

$$Z = A_2 \exp(\beta\sigma) \tag{3}$$

$$Z = A_3 [\sinh(\alpha\sigma)]^n \tag{4}$$

A_1, A_2, A_3, n', β, α and n in the above three models are dimensionless constants related to the material state. α is the stress level parameter, n is the stress index under different stress levels, and A_1, A_2, A_3 is the material structure factor.

In order to facilitate the determination of the relation-ship between the parameters of the equation, Formula (2) and Formula (3) are substituted into Formula (1) respectively, and the logarithms are taken on both sides of the obtained formula. The following equation can be obtained:

$$\ln \dot{\varepsilon} = \ln A_1 + n' \ln \sigma - \frac{Q}{RT} \quad (5)$$

$$\ln \dot{\varepsilon} = \ln A_2 + \beta\sigma - \frac{Q}{RT} \quad (6)$$

By substituting the peak stress into formula (5) and formula (6) respectively, the linear regression curves of $\ln \dot{\varepsilon} - \ln \sigma$ and $\ln \dot{\varepsilon} - \sigma$ are obtained, which are shown in Figure 2 and Figure 3 respectively.

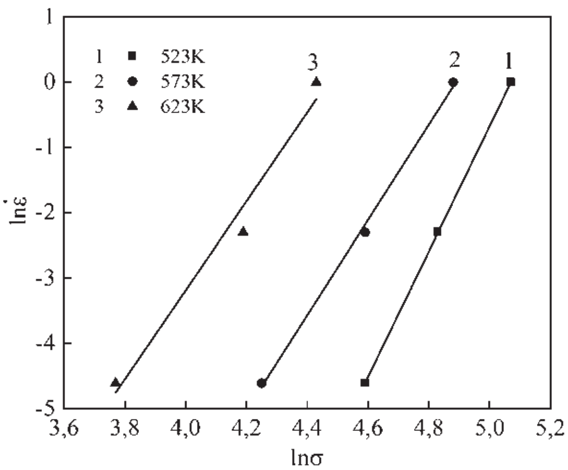

Figure 2 Relation curves of $\ln\dot{\varepsilon}$ and $\ln\sigma$

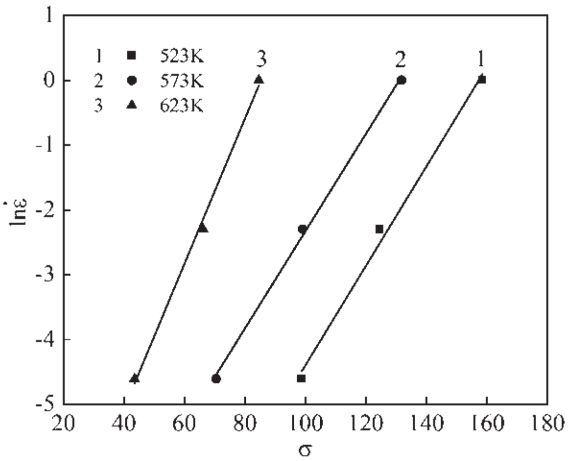

Figure 3 Relation curves of $\ln\dot{\varepsilon}$ and σ

The values of n' and β can be obtained from the figure, and the average value of the slope of the regression line is calculated to obtain $n' = 7{,}908$, $\beta = 0{,}0879$; Then calculate the value of α, $\alpha = \beta / n'$, so $\alpha = 0{,}0111$.

Substituting Formula (4) into Formula (1) and taking logarithms on both sides:

$$\ln \dot{\varepsilon} = \ln A_3 + n \ln[\sinh(\alpha\sigma)] - \frac{Q}{RT} \quad (7)$$

It can be seen that when the temperature is cons-tant, $\ln \dot{\varepsilon}$ and $\ln[\sinh(\alpha\sigma)]$ show a certain linear relationship:

$$n = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]} \quad (8)$$

Similarly, when the strain rate is constant, $\ln[\sinh(\alpha\sigma)]$ and $1 / T$ have a certain linear relationship:

$$\frac{Q}{nR} = \frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial(1/T)} \quad (9)$$

Substitute the data into formula (8) and formula (9), and perform linear fitting regression on them respectively to obtain $\ln\dot{\varepsilon} - \ln\left[\sinh\left(\alpha\sigma\right)\right]$ and $\ln\left[\sinh\left(\alpha\sigma\right)\right] - \left(1/T\right)$ linear regression curves, as shown in Figure 4 and Figure 5 respectively.

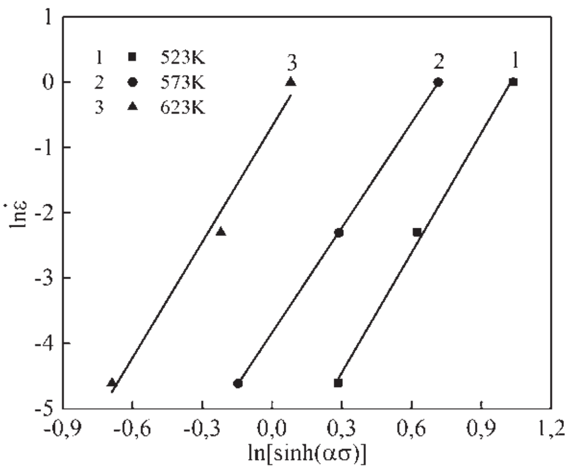

Figure 4 Relation curves of $\ln\dot{\varepsilon}$ and $\ln[\sinh(\alpha\sigma)]$

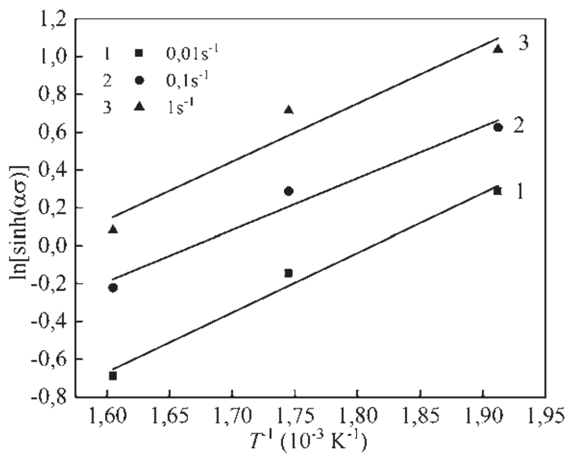

Figure 5 Relation curves of $\ln[\sinh(\alpha\sigma)]$ and $1 / T$

The values of n and Q / nR can be obtained from the figure, and n = 5,7922, Q / nR = 2990,681 can be obtained by calculating the average value of the slope of the regression line respectively, so Q = 144 015,31 J / mol.

Taking the logarithm on both sides of Formula (4):

$$\ln Z = n \ln[\sinh(\alpha\sigma)] + \ln A_3 \quad (10)$$

According to Formula (10), the relationship curve of $\ln Z - \ln\left[\sinh\left(\alpha\sigma\right)\right]$ is shown in Figure 6. After linear regression, the intercept value $\ln A_3 = 26{,}9358$ of the straight line is obtained, so $A_3 = 4{,}9896 \times 10^{11}$.

Finally, the calculated A_3, α, Q and n are substituted into Formula (4) to obtain the peak stress constitutive equation of Mg-Zn-Zr-Y alloy.

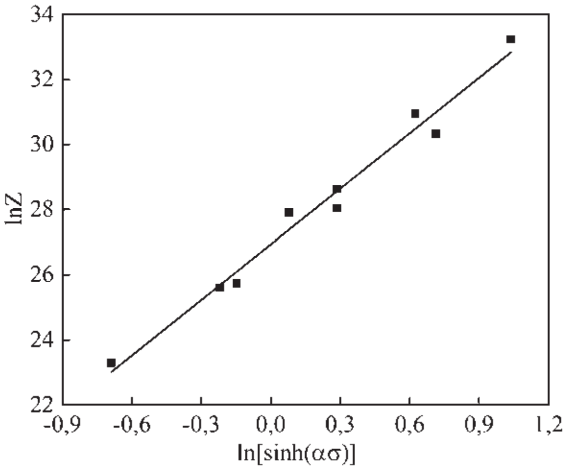

Figure 6 Relation curves of lnZ and ln[sinh($\alpha\sigma$)]

$$\dot{\varepsilon} = 4,9896 \times 10^{11}[\sinh(0,0111\sigma)]^{5,7922} \exp\left(-\frac{144\ 015,31}{8,314T}\right) \quad (11)$$

SIMULATION PREDICTION AND VERIFICATION OF CONSTITUTIVE MODEL

The corresponding test conditions are substituted into Formula (11), and the calculated results are compared with the experimental data. As shown in Figure 7, the maximum relative error between the calculated results and the measured values of the constitutive model of Mg-Zn-Zr-Y alloy during high temperature compression deformation is 9,45 %, and the average relative error is 5,67 %. The established model can predict the peak stress of the material well.

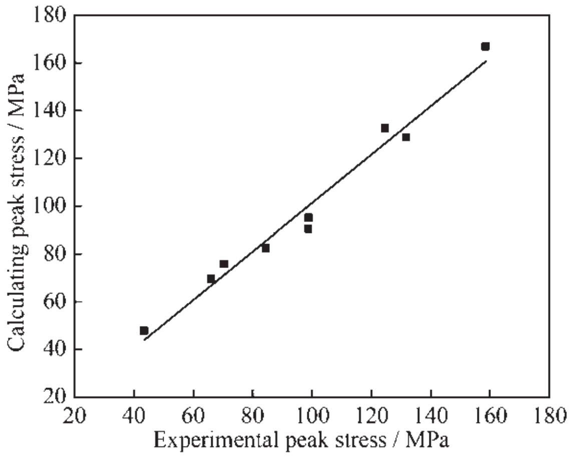

Figure 7 The peak stress calculation results are compared with the measured values.

CONCLUSION

In this paper, the constitutive relationship of Mg-Zn-Zr-Y alloy at different temperatures and different strain rates was studied. By introducing the strain compensation factor Z parameter, the Arrhenius constitutive model of Mg-Zn-Zr-Y alloy in the expected strain range was established, and the accuracy and feasibility of flow stress prediction were analyzed and verified. The results show that the constitutive model established in this paper has high accuracy, which can provide basis and reference for the study of plastic deformation of magnesium alloy.

REFERENCES

[1] W. C. Pei, W. Q. Wu, Y. Hu, et al. High temperature constitutive model of Q345B steel [J]. Metalurgija 61 (2022), 3-4, 681-684.

[2] X. S. Li, J. Chen, H. B. Zhang. Constitutive model for hot deformation of 6082 aluminum alloy [J]. The Chinese Journal of Nonferrous Metals 18 (2008), 1769-1774.

[3] C. Wang, Z. Y. Yu, Z. T. Yu, et al. Thermal deformation behavior of Mg-3Zn-1Zr alloy and its constitutive model [J]. Light Metals 12 (2018), 40-44.

[4] G. Q. You, F. J. Yao, Q. Li, et al. Research progress of powder metallurgy magnesium-based materials [J]. Rare Metal Materials and Engineering 51 (2022), 3497-3509.

Note: The responsible translator for English language is Y Y Jin-North China University of Science and Technology, China