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A Study on the Phenomenological Constitutive Model of Mg-12Gd-5Y-3Zn-0.6Zr Magnesium Alloy Forming at Elevated Temperature

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Abstract. Quantities Mg-12Gd-5Y-3Zn-0.6Zr magnesium alloy billets were compressed with true strain 0.7 on hot process simulator at 350,400,450,480°C under strain rates of 0.001, 0.01, 0.1 and $0.5s^{-1}$. A constitutive model with a few parameters is used to characterize the dynamic recrystallization strain softening of Mg-12Gd-5Y-3Zn-0.6Zr alloy, which comprehensively reflect the effects of the deformation temperature, strain and strain rate on flow stress.

Introduction

For the metal charactering dynamic recrystallization, because of its complexity of flow curves, flow stress model should not only reflect the rising of curve caused by the work hardening, but also reflect the dropping and then tending to smooth stage of curve caused by the dynamic recrystallization. Many researchers find it difficult to adopt an independent equation using a few parameters to establish the flow stress model [1-2].

Magnesium alloy is the lightest mental material available for industrial application now, and has many good mechanical properties, such as high specific strength, excellent performance on vibration damping and electromagnetic shielding, and high specific stiffness, etc. Thus, high–performance magnesium has so far been widely used in the fields like top aerospace industry, automobile industry and military industry. Serious lack of some corresponding research about the plastic deformation of magnesium alloy at elevated temperatures, such as predicting and preventing fracture, determining the processing parameters, etc. made magnesium alloy component processed by plastic deformation to be rare [3].

In this study, an equation with a few parameters to characterize the flow stress model of the Mg-12Gd-5Y-3Zn-0.6Zr alloy, which comprehensively reflect the deformation temperature, strain and strain rate on flow stress, and including dynamic recrystallization strain softening.

Experimental materials and methods

Mg-12wt%Gd-5wt%Y-3wt%Zn-0.6wt%Zr alloy ingots are adopted as the materials for experiment. Firstly, intercept along the axial direction from the ingot a piece of slab with a thickness of 15mm. Secondly, heat the slab to 520°C and insulate it for 4 hours and air-cool it to room temperature. A computer-controlled, servo-hydraulic Gleeble3800 machine was used for compression testing. The homogenized ingot was scalped to diameter of 10mm and height of 15 mm with grooves on both sides filled with machine oil mingled using graphite powder as lubrication during isothermal hot compression tests at 350, 400, 450 and 480°C with a strain rate of 0.001, 0.01, 0.1 and 0.5s-1, respectively.

True stress-true strain curves. The true compressive stress-strain curves of Mg-12Gd-5Y-3Zn-0.6Zr magnesium alloy are shown in Fig.1.The flow stress as well as the shape of the flow curves is sensitively dependent on temperature and strain rate. For all of specimens, after initial yielding, the flow stress decreases monotonically with different softening rates. For a specific strain rate, the flow stress decreases markedly with the increase of temperature, while for a specific temperature, the flow stress increases markedly with the increase of strain rate. Only for temperature of 300°C, fracture is seen to occur after a dynamic softening.

The Phenomenological Constitutive Model including Dynamic Recrystallization Softening. One of the most significant characteristics of the high temperature deformation is that the deformation is controlled by a thermal activation process. Sellars [4] consider that the steady-state flow stress of the thermal deformation depends on the deformation temperature and the strain rate, which can be express by the creep equation:

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

Where Z is the Zener-Hollomon parameter; $\dot{\varepsilon}$ is the strain rate; Q is the deformation activation energy; σ is the steady-state flow stress; R is the gas constant, 8.31J • mol^{-1}•K^{-1}; T is the temperature; A, α, n are undetermined constants.
The relationship among peak stress, peak strain and Z. The researchers [5] regard Eq.(5) as following if the stress value is low:

$$Z = \dot{\varepsilon}\exp\left(Q/RT\right) = A[\sinh(\alpha\sigma)]^n \approx C_1\sigma^{n'}. \tag{2}$$

The researchers [5] regard Eq.(5) as following if the stress value is high:

$$Z = \dot{\varepsilon}\exp\left(Q/RT\right) = A[\sinh(\alpha\sigma)]^n \approx C_1\sigma^{n'}. \tag{3}$$

Where C_1, C_2, β and n' are undetermined constants. The approximate α is:

$$\alpha = \beta / n'. \tag{4}$$

An expression of Q is as follows [5]:

$$Q = R\left[\frac{\partial(\ln(\sinh(\partial\sigma)))}{\partial\left(1/T\right)}\right]_{\varepsilon} \cdot \left[\frac{\partial\ln\dot{\varepsilon}}{\partial(\ln(\sinh(\alpha\sigma)))}\right]_T. \tag{5}$$

From the study of McQueen [6], it is feasible to regard the peak stress σ_p as σ_p for calculations of Eq.(2) and Eq.(3). So, n' can be obtained by plotting $\ln\dot{\varepsilon} - \ln\sigma_p$ curve (see Fig.2a); β can be obtained by plotting $\ln\dot{\varepsilon} - \ln\sigma$ curve (see Fig.2b); α can be obtained from Eq.(4). Q can be obtained by plotting $\ln[\sinh(\alpha\sigma_p)] - 1/T$ (see Fig.3a) and $\ln[\sinh(\alpha\sigma_p)] - \ln\dot{\varepsilon}$ (see Fig.2b) curves. Z can be obtained by bringing Q into Eq.(1), the perfect A and n values can be obtained from the relationship between $\ln Z - \ln[\sinh(\alpha\sigma_p)]$ (see Fig.4).

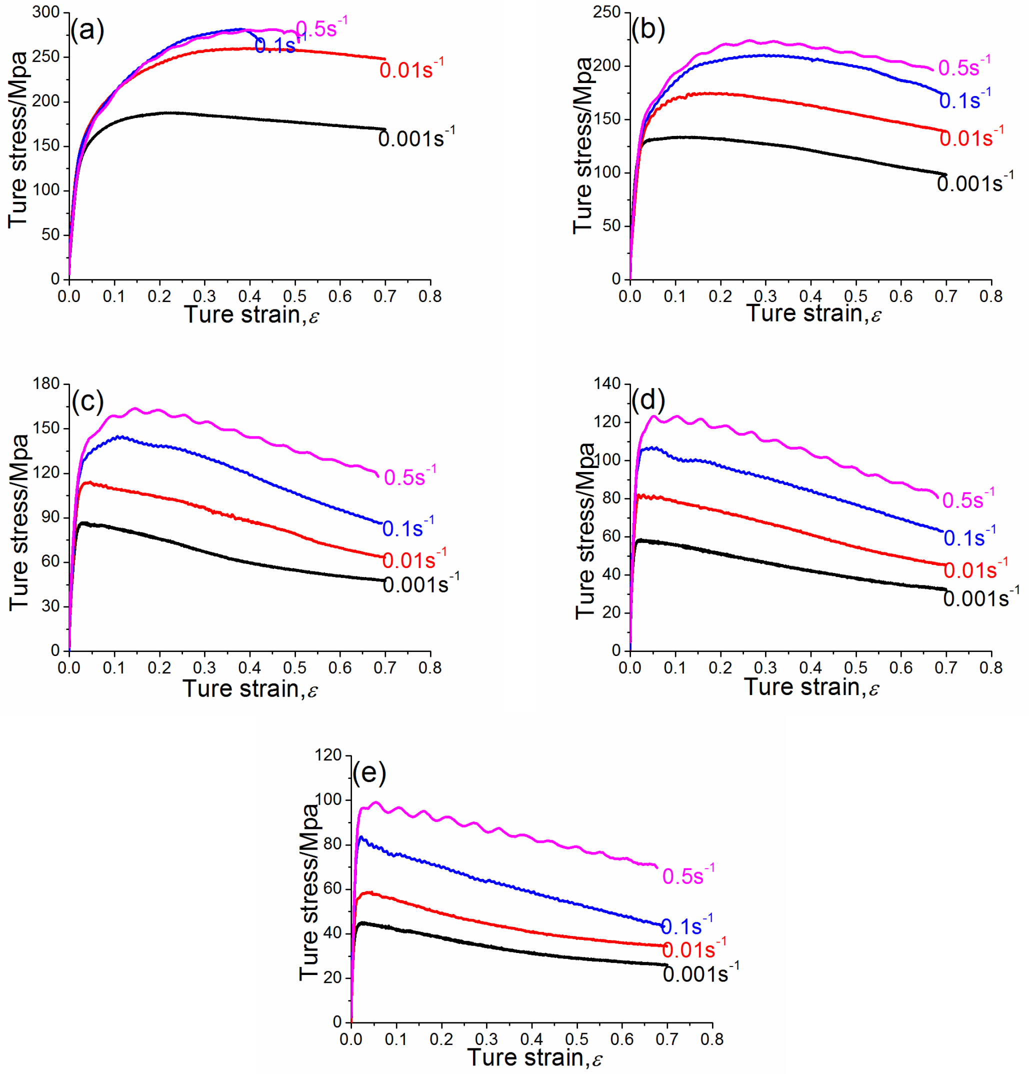

Fig. 1 Compressive true stress-strain curves for Mg-12Gd-5Y-3Zn-0.6Zr alloy at different test:(a)300°C; (b)350°C; (c)400°C; (d)450°C; (e)480°C;

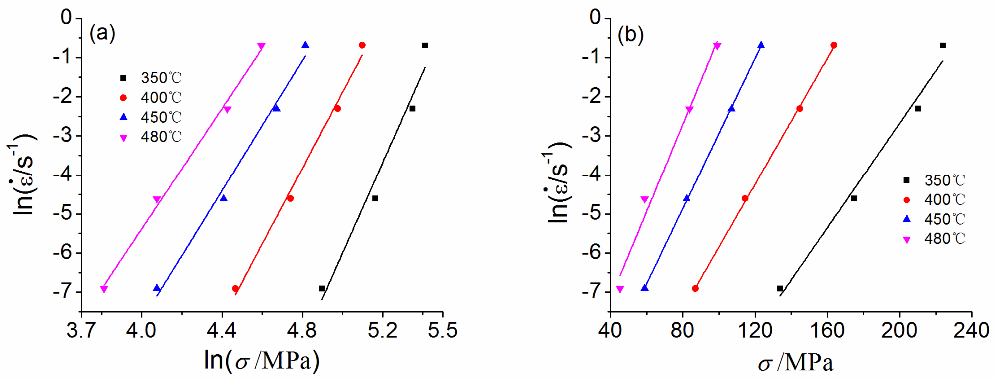

Fig.2 The relationships between σ_p and $\dot{\varepsilon}$:(a) $\ln\dot{\varepsilon}-\ln\sigma_p$;(b) $\ln\dot{\varepsilon}-\ln\sigma_p$

Using a least squares linear regression, it can be obtained as following: n=6.81966, β=0.07364, α=0.009205, A =3.049×10^{18} and Q=273.42kJ/mol.

When calculating the softening caused by the dynamic recrystallization during hot deformation, the peak strain ε_p would be used, in order to establish the following expression at any time, according to the relationship between $\ln Z-\ln\varepsilon_p$ (see Fig.5), it is suitable to regard the peak strain and Z as follows:

$$\ln\varepsilon_p = C_1 \ln Z + C_2 . \quad (6)$$

Where C_1 is 0.17048; C_2 is -7.22652.

The relationship between flow stress and stress and strain peak. In order to analyze the softening caused by the dynamic recrystallization, considering the relationship between the difference of stress and stress peak and the strain at the moment, this study found that if the strain is multiplied by a coefficient and all values are logarithmic, shown in Fig.6a. It can be seen from the figure at the different temperature and strain rate conditions, distribution curve was a quadratic function approximately. According to Lagrange mean value theorem, use the least square to fit a ratio between the value of $\ln\sigma - \ln\sigma_p$ and $\ln\zeta\varepsilon$, then Fig.6b can be obtained. It can be found that a curve linear relationship occurs at the different temperature and strain rate.

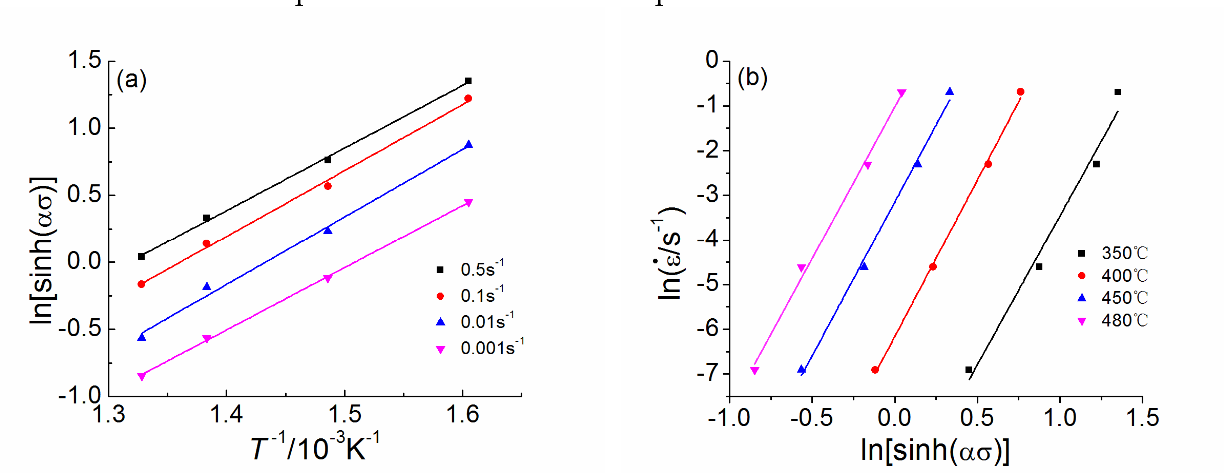

Fig.3 The relationships among $\ln\sigma_p$, T and $\dot{\varepsilon}$:

(a) $\ln[\sinh(\alpha\sigma_p)] - 1/T$; (b) $\ln[\sinh(\alpha\sigma_p)] - \ln\dot{\varepsilon}$

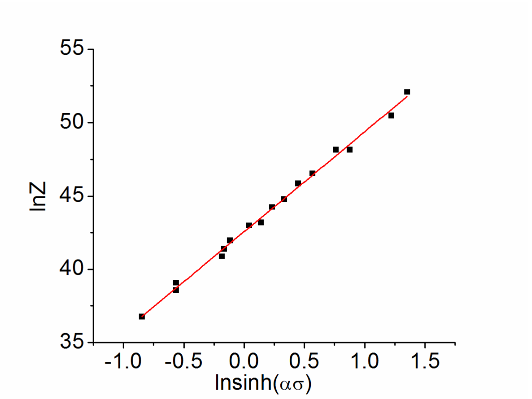

Fig.4 The relationship between σ_p and Z

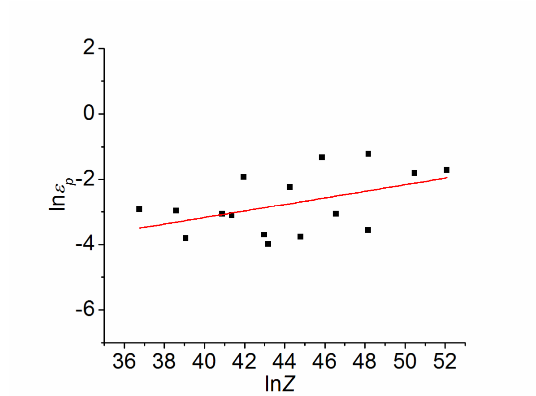

Fig.5 The relationship between ε_p and Z

According to the law of Fig6a, in order to facilitate the following derivation, a 'softening- factor' was introduced, which was defined as [6]:

$$\eta^* = \frac{\ln\sigma - \ln\sigma_p}{\ln(\zeta\varepsilon)} . \quad (7)$$

After analysis, it can be found that, when ζ is less than or equal to 0.7, η^* and ε meet the following equation well:

$$\frac{\ln\sigma - \ln\sigma_p}{\ln(\zeta\varepsilon)} = \omega\left(\frac{\varepsilon - \varepsilon_p}{\varepsilon_p}\right)^2 . \quad (8)$$

The above equation can be rewritten as:

$$\ln\sigma = \lambda(\varepsilon - \varepsilon_p)^2 \ln\zeta\varepsilon + \ln\sigma_p . \tag{9}$$

Where $\partial\eta^* / \partial\varepsilon = a\varepsilon - b$ (see Fig.5b), $\omega = b^2/2a , \lambda = a/2$.
Theoretically, the equation with two unknowns can be solved just needing two equations. There are so many data Obtained from hot compression tests that ζ and η^* to be fitted by the least squares regression method. The fitting results: ζ is 0.6815, λ is 1.5980. According to the formula (11), when $\dot{\varepsilon}$ = 0.01s^{-1}, the comparison between the predicted flow stress and the experimental data is shown in Fig.7. The Fig.7 shows that predicted values form the model is in good agreement with the experimental values.

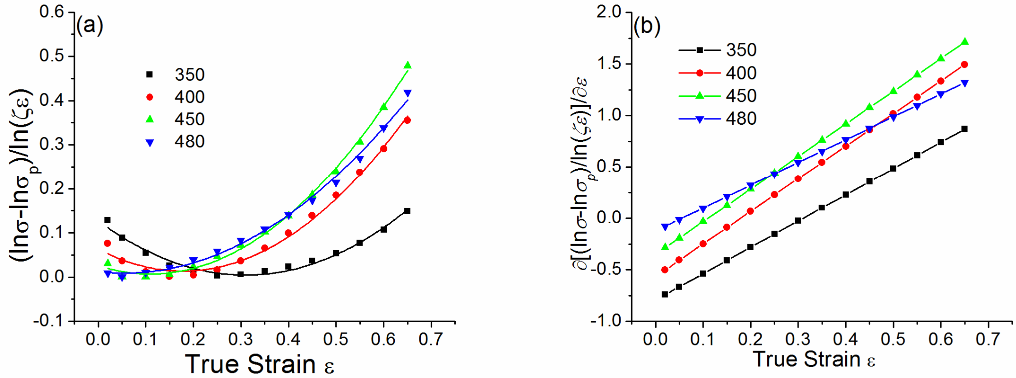

Fig.6 The relationships among $(\ln\sigma - \ln\sigma_p)/\ln\zeta\varepsilon$, $\partial[(\ln\sigma - \ln\sigma_p)/\ln\zeta\varepsilon]/\partial\varepsilon$ and ε: (a) $(\ln\sigma - \ln\sigma_p)/\ln\zeta\varepsilon - \varepsilon$; (b) $\partial[(\ln\sigma - \ln\sigma_p)/\ln\zeta\varepsilon]/\partial\varepsilon - \varepsilon$

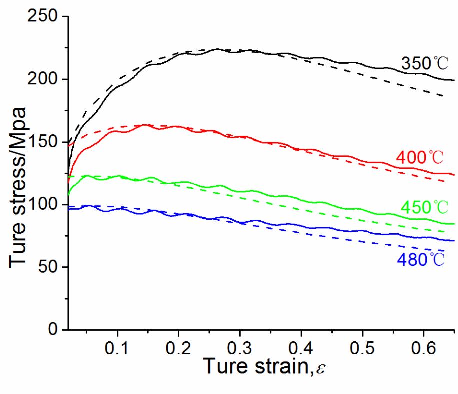

Fig.7 Comparison of modeling calculated results with experimental result for flow stress of Mg-12Gd-5Y-3Zn-0.6Zr alloy (dashed curves denote modeling calculated results)

Conclusions

In order to take the influence of strain, deformation temperature and strain rate on flow stress of Mg-12Gd-5Y-3Zn-0.6Zr alloy into account, a constitutive model of the Mg-12Gd-5Y-3Zn-0.6Zr magnesium alloy with dynamic recrystallization on the basis of the creep equation was established, as follows:

$$\ln\sigma = \lambda(\varepsilon - \varepsilon_p)^2 \ln\zeta\varepsilon + \ln\sigma_p .$$

Where:

$$\sigma_p = \frac{1}{\alpha} \cdot \ln \left\{ \left(\frac{Z}{A} \right)^{\frac{1}{n}} + \left[\left(\frac{Z}{A} \right)^{\frac{2}{n}} + 1 \right]^{\frac{1}{2}} \right\}, \quad Z = \dot{\varepsilon} \exp\left(Q/_{RT} \right), \quad \ln \varepsilon_p = C_1 \ln Z + C_2 .$$

Where α=0.009205, Q=273.42kJ/mol, n=6.81966, A=3.049×1018, C_1=0.17048, C_2=-7.22652, ζ=0.6815, λ=1.5980 .

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