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ARTICLE

Dynamics and Kinematics Models of Dynamic Recrystallization of AZ80 Magnesium Alloy During Thermal Deformation

Wang Zhongtang, Jiang Jihao, Liu Xunan, Yu Xiaolin

Shenyang Ligong University, Shenyang 110159, China

Abstract: The stress-strain curves of AZ80 magnesium alloy were tested by thermal simulation experiment. The deformation temperature ranged from 533 K to 683 K, the strain-rate was 0.001~10 s^{-1}, and the deformation degree was 50%. The results show that the grain size of dynamic recrystallization (DRX) increases with raising the deformation temperature and reducing the strain-rate. According to the Arrhenius equation and experiment data, the energy of thermal activation of AZ80 magnesium alloy is determined, and a kind of constitutive equation of AZ80 magnesium alloy is established. According to the Sellars equation, the dynamics model of AZ80 magnesium alloy is established, which is defined as the relationship between the volume fraction of DRX and deformation temperature and strain-rate. The kinematics model of AZ80 magnesium alloy is established, which is defined as the relationship between grain size of DRX and deformation temperature and strain-rate. The calculated results of grain size of DRX are in agreement with the experiment results, and relative errors are less than 11.8%. The mathematical model between critical strain and steady strain of DRX with deformation temperature and strain-rate are established.

Key words: magnesium alloy; AZ80; dynamic recrystallization; dynamics model; kinematics model

AZ80 magnesium alloy has high strength and good corrosion resistance, so the application field of AZ80 magnesium alloy can be more extensive. When AZ80 magnesium alloy is extruded at 330 °C, the microstructure is uniform equiaxed grain and the grain size is about 6 μm. When AZ80 magnesium alloy is extruded at 380 °C, the tensile strength reaches 400 MPa and the elongation is 8%[1]. The microstructure and mechanical properties of AZ80 magnesium alloy are improved by cyclic expansion (CEEOP) deformation process [2]. Zhao [3] found that the incomplete dynamic recrystallization of ZAT422 alloy occurs when deformation temperature is lower than 498 K and the strain is 0.9163. When the deformation temperature rises to 648 K, the lower strain rate will lead to abnormal growth of some grains. Chang [4] found that the flow stress fluctuates evidently in loading direction of 90° when AZ80 magnesium alloy is deformed at multiple loading directions and strain rates. Bhattacharyya[5] found that the texture and grain growth of rolled AZ31 magnesium alloy are influenced by parameters during annealing process. Because of the coordination of twinning and slip during the cold rolling process, the plastic deformation properties of magnesium alloy can be improved [6]. During extrusion process of Mg-6Sn alloy, the deformation conditions have a great influence on the grain size, recrystallization rate and dynamic precipitation rate of the alloy. Their texture strength decreases with the increase of extrusion speed and deformation temperature [7]. When AZ31 magnesium alloy is deformed by compression process at room temperature, the critical shear stress (CRSS) of the tensile twin is larger than that of the base plane. With the increase of grain boundary angle, the tensile twinning increases[8]. A quantitative relationship between the correlation parameters and the actual deformation conditions in cellular automata method (CA) is established, which predicts the dynamic recrystallization (DRX) grain size of magnesium alloy.

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Corresponding author: Wang Zhongtang, Ph. D., Professor, School of Material Science & Engineering, Shenyang Ligong University, Shenyang 110159, P. R. China, Tel: 0086-24-24680841, E-mail: ztwang@imr.ac.cn

The fine and uniform initial microstructure is conducive to the dynamic recrystallization process of magnesium alloy during hot deformation [9]. At the beginning of the yielding of magnesium alloy, the slip of the matrix dislocation is the main factor for the plastic strain, but the twin nucleation has been activated. The contribution of twinning increases rapidly with the increase of plastic strain [10]. The plastic deformation mode of AZ31 magnesium alloy changes from the main twin and a small number of dislocations to the enhancement of the non-base surface slip and the dynamic recrystallization (DRX) to weaken twins. At the same time, the fracture mode also occurs in the dynamic recrystallization from the grain boundary (GBS) and the twin boundary (TBS) or the double end to the nearby GBS [11]. Kim [12] studied the thermal compression rheological behavior of Mg-9.5Zn-2.0Y alloy, analyzed the plastic deformation mechanism, and established the material constitutive equation. During extrusion deformation of ZK60 magnesium alloy, the loading direction and the initial material orientation have a significant influence on the rheological stress and the strain hardening rate. The deformation mechanisms associated with strain hardening rate at different stages were discussed with a particular emphasis on the roles of deformation twinning [13]. During multi-pass rolling deformation of ZK60 magnesium alloy sheet at low temperature, the dynamic recrystallization (DRX) occurred, and the grain size was obviously refined, and the uniformity of microstructure was significantly improved [14]. During deformation of AZ31B magnesium alloy, the pre-compressive strain remarkably affects the reverse tensile yield stress and the width of the detwinning-dominant stage during inverse tension process [15].

1 Stress-Strain Curves

MMS-200 thermal simulator was used to test the true stress-strain curves of AZ80 magnesium alloy by thermal simulation experiment. The experiment deformation temperature was 533~683 K, the strain-rate was 0.001~10 s^{-1}, and the reduction was 50%. The true stress-strain curves at different conditions are shown as Fig.1.

2 Microstructure Evolution

Scanning electron microscope (SEM) (S-3400N), inverted microscope Axioert (200MAT), quantitative metallographic test instrument Tecnai (G220), high temperature microscope Axiophoto, and X-ray diffraction (XRD-7000S/L) were used to test microstructures and grain size.

The microstructure of AZ80 magnesium alloy deformed at different strain rates is shown in Fig.2. Dynamic recrystallization occurs more completely and the grain size decreases with increasing the strain rate. The first reason is that the large strain rate will result in dislocation aggregation and accelerate dynamic recrystallization start-up. The second reason is that the low strain rate will cause enough time for crystal boundary migration and increase the growth time for grain of DRX. So,

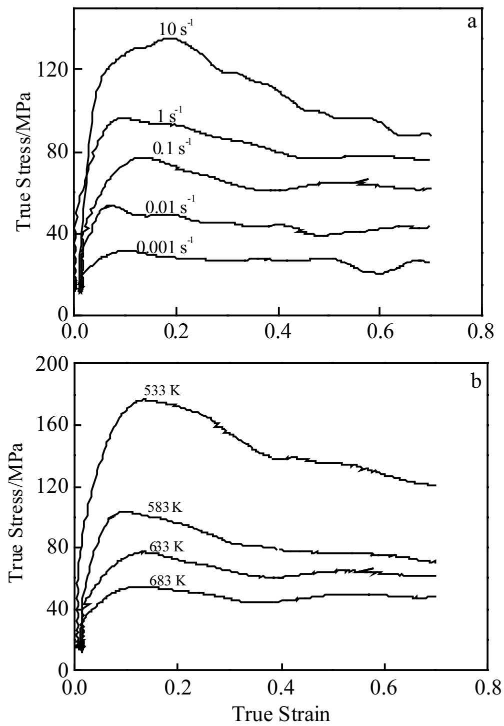

Fig.1 True stress-strain curves of AZ80 magnesium alloy at a deformation temperature of 633 K (a) and a strain rate of 0.1 s^{-1} (b)

high strain rate is favorable for refining grain. But when strain rate is too high, twin crystal and coarse crystal and mixed crystal will appear. The curve of grain size vs strain rate is shown in Fig.2e.

Microstructures of dynamic recrystallization of AZ80 magnesium alloy at different temperatures are shown in Fig.3. The grain size increases with increasing the deformation temperature. The reason is that the mobility of grain boundaries increases at high temperature. The curve of grain size vs deformation temperature is shown in Fig.3e.

3 Constitutive Model

Sellars [16] proposed a hyperbolic-sinusoid model which includes energy (Q) of thermal activation and temperature (T). Arrhenius equation can be written as Eq. (1):

$$\left.\begin{aligned} \dot{\varepsilon} &= A_1\sigma^n \exp\left(-\frac{Q}{RT}\right) & \alpha\sigma \le 0.5 \\ \dot{\varepsilon} &= A_2 \exp(\alpha n\sigma)\exp\left(-\frac{Q}{RT}\right) & \alpha\sigma > 1.6 \\ \dot{\varepsilon} &= A\left[\sinh(\alpha\sigma)\right]^n \exp\left(-\frac{Q}{RT}\right) & \text{All value} \end{aligned}\right\} \quad (1)$$

In which, $A_1=A\alpha^n$, $A_2=A2^{-n}$, $\dot{\varepsilon}$ is strain rates (s^{-1}), Q is energy of thermal activation (J/mol), σ is flow stress (MPa), T is deformation temperature (K), R is constant, R=8.314 J/(mol·K), and A, α and n are constants independent of temperature.

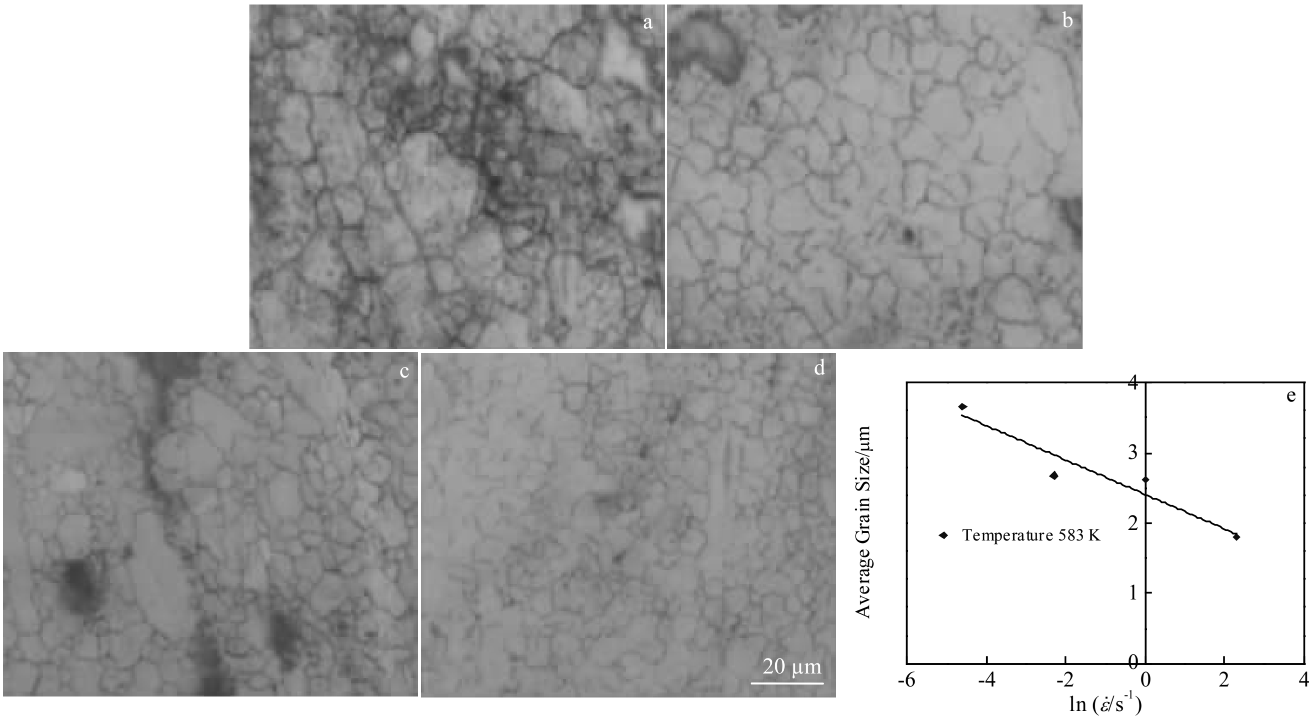

Fig.2 Microstructures of AZ80 alloy at deformation temperature of 583 K under different strain rates: (a) 0.01 s^{-1}, (b) 0.1 s^{-1}, (c) 1 s^{-1}, and (d) 10 s^{-1}; (e) average grain size vs strain rate

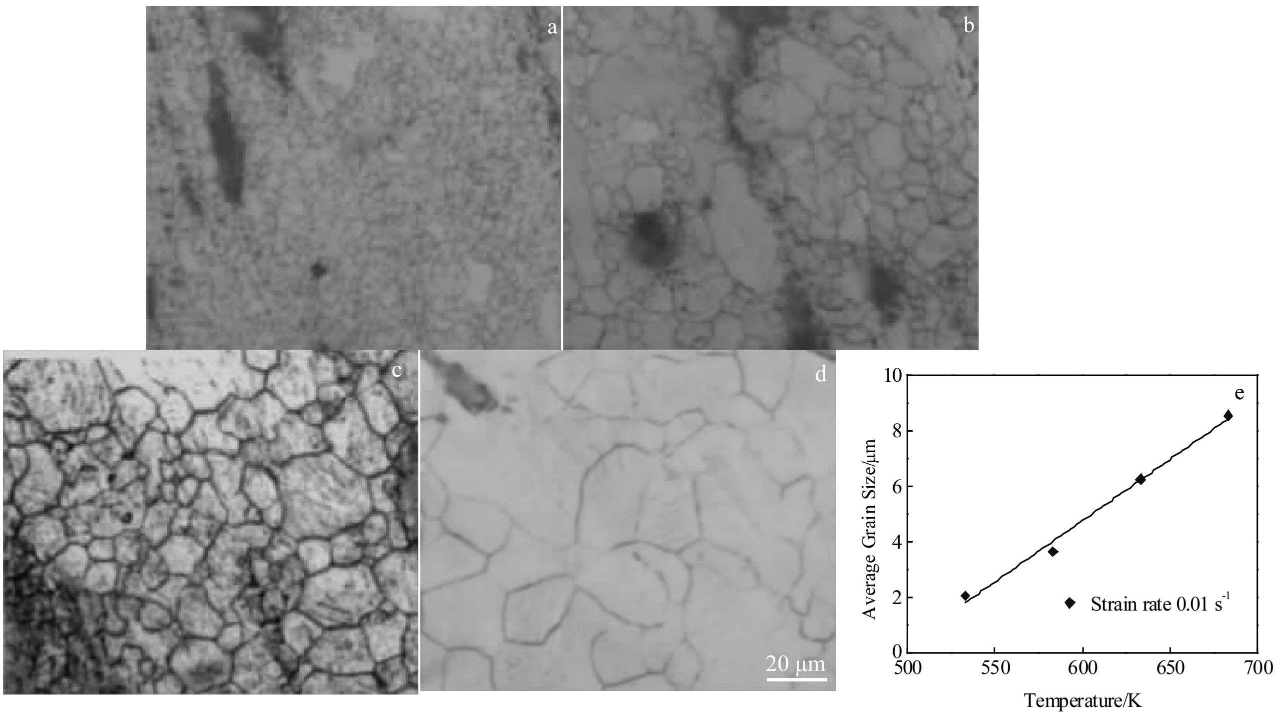

Fig.3 Microstructures of AZ80 alloy at strain rate of 0.01 s^{-1} and different temperatures: (a) 533 K, (b) 583 K, (c) 633 K, and (d) 683 K; (e) average grain size vs deformation temperature

The constitutive relation model was determined based on the peak stress (σ_p). According to the experimental data, the curves of $\ln\dot{\varepsilon}$ - $\ln\sigma_p$ and $\ln\dot{\varepsilon}$ - σ_p and $\ln[\sinh(\alpha\sigma_p)]$ - $1/T$ are shown in Fig.4. According to Eq.(1), the coefficients (*n, α, Q, A*) can be determined as n=6.6625, α=0.01238, Q=140671 J/mol, A=1.019×10^{20}, A_1=19.15×10^6, and A_2=1.006×10^{18}. Taking the coefficients to Eq.(1), the constitutive equation of AZ80 magnesium alloy can be expressed as Eq.(2).

$$\left.\begin{aligned} &\dot{\varepsilon}=19.15\times10^{6}\sigma^{6.6625}\exp\left(-\frac{140671}{RT}\right) && \alpha\sigma<0.5 \\ &\dot{\varepsilon}=1.006\times10^{18}\exp(0.0825\sigma)\exp\left(-\frac{140671}{RT}\right) && \alpha\sigma>2.0 \\ &\dot{\varepsilon}=1.019\times10^{20}\left[\sinh(0.01238\sigma)\right]^{6.6625}\exp\left(-\frac{140671}{RT}\right) && \text{All value} \end{aligned}\right\} \quad (2)$$

4 Dynamics Model of DRX

The dynamics model describes the relationship between the volume fraction of dynamic recrystallized grains (X) and deformation temperature (T) and function Z and strain-rate ($\dot{\varepsilon}$). The kinematics model describes the relationship between grain size (d) of DRX and function Z.

According to the results of experiment, the curves of the volume fraction of dynamic recrystallized grains (X) and deformation temperature (T) and function Z and strain-rate are obtained. Based on the analysis of the experimental data, it is found that the volume fraction of dynamic recrystallized grains (X) increases with raising the deformation temperature and reducing the strain-rate and ln(Z). Karhausen[17] proposed the relationship model of the volume fraction of dynamic recrystallized grains (X) and critical conditions, shown as Eq.(3) and (4).

$$X = 1 - \exp\left[-k_4\left(\frac{\varepsilon-\varepsilon_c}{\varepsilon_s-\varepsilon_c}\right)^{n_3}\right] \quad (3)$$

$$\varepsilon_p = k_1 Z^{n_1},\ \varepsilon_c = k_2\varepsilon_p,\ \varepsilon_{st} = k_3 Z^{n_2} \quad (4)$$

in which, X is the volume fraction of dynamic recrystallized grains (%), ε is strain, ε_p is the strain corresponding to peak stress (σ_p), ε_c is critical strain at which dynamic recrystallization occurs, ε_{st} is strain when dynamic recrystallization completely occurs, k and n are coefficients, k_1~k_5 and n_1~n_4 are constants, Z is function of Zener-Hollomon, $Z=\dot{\bar{\varepsilon}}\exp(Q/RT)$, Q is energy of thermal activation (J/mol), R is constant (R=8.314 J/(mol·K)), T is deformation temperature (K), and $\dot{\bar{\varepsilon}}$ is equivalent strain rate.

According to the stress-strain curves shown in Fig.1, the peak strain (ε_p), peak stress (σ_p) and steady strain (ε_{st}) can be determined. And the coefficient k_2 in Eq.(4) can be given by experience equation ε_c=(0.65~0.85)ε_p, and results are k_2=0.75, and ε_c=0.75ε_p[18].

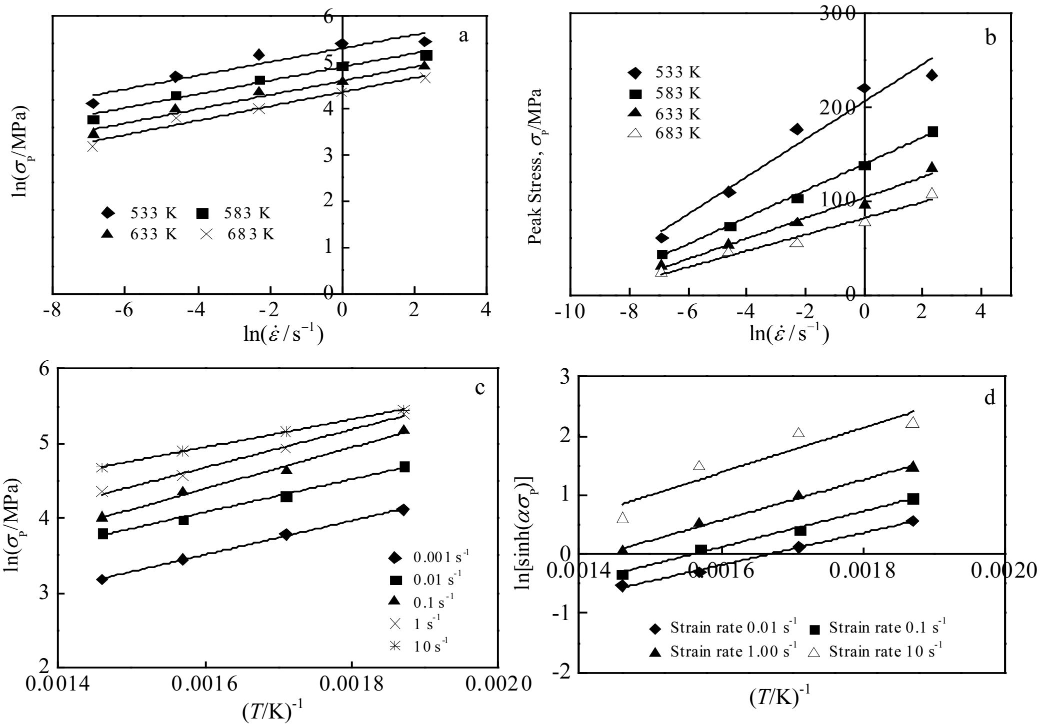

Fig.4 Curves of peak stress and strain and deformation temperature: (a) $\ln\sigma_p$-$\ln\dot{\varepsilon}$, (b) σ_p-$\ln\dot{\varepsilon}$, (c) $\ln(\sigma_p)-1/T$, and (d) $\ln[\sinh(\alpha\sigma_p)]-1/T$

According to the value of ε_p, ε_c and Eq.(4), the value of n_1 and k_1 can be determined by Eq.(5) to be n_1=0.083 and k_1=2.235×10^{-3}, respectively.

$$n_1 = \frac{\partial \ln \varepsilon_p}{\partial \ln Z}, \quad k_1 = \frac{\varepsilon_p}{Z^{n_1}} \tag{5}$$

According the value of ε_{st} and Eq.(4), the value of n_2 and k_3 can be determined by Eq.(6). The results are n_2=0.118 and k_3=0.0027.

$$n_2 = \frac{\partial \ln \varepsilon_s}{\partial \ln Z}, \quad k_3 = \frac{\varepsilon_p}{Z^{n_2}} \tag{6}$$

According to the stress-strain curves shown in Fig.1, the coefficients n_3 and k_4 in Eq.(3) can be determined to be n_3=2.231 and k_4=1.803, respectively. The dynamics model of AZ80 magnesium alloy is obtained, as shown in Eq.(7).

$$X = 1 - \exp\left[-1.803\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_{st} - \varepsilon_c}\right)^{2.231}\right] \tag{7}$$

Relationships between the peak strain (ε_p), function Z, critical strain ε_c of DRX and steady strain ε_{st} are expressed as Eq.(8).

$$\left.\begin{aligned} \varepsilon_p &= 1.68\times10^{-3} Z^{0.083} \\ \varepsilon_{st} &= 0.0027 Z^{0.118} \end{aligned}\right\} \tag{8}$$

$$\varepsilon_c = 0.75\varepsilon_p, \quad Z = \dot{\varepsilon}\exp\left(\frac{140671}{RT}\right)$$

5 Kinematics Model of DRX

The kinematics model illustrating the relationship between grain size and function Z is given as Eq.(9).

$$d = k_5 Z^{n_4}, \quad \bar{d} = (1 - X)d_0 + Xd \tag{9}$$

in which, d_0 is original grain size (μm), d is grain size of DRX (μm), and $\bar{d}$ is average grain size of DRX (μm).

According to the experiment results of grain size of DRX, shown in Fig.2, Fig.3 and Eq.(9), the value of n_4 and k_5 can be determined by Eq.(10). The results are n_4=–0.113 and k_5=402.9.

$$n_4 = \frac{\partial \ln d}{\partial \ln Z}, \quad k_5 = \frac{d}{Z^{n_4}} \tag{10}$$

According to experiment results, the original grain size of AZ80 alloy is 60 μm, and average grain size ($\bar{d}$) can be determined by Eq.(9). According to experiment data, the microstructure evolution model of AZ80 magnesium alloy is obtained under the condition of original grain size of 60 μm, strain rate of 0.001~10 s^{-1}, and deformation temperature of 533~683 K. The kinematics model describing the relationship between grain size and function Z is obtained, shown as Eq.(11).

$$d = 402.9 Z^{-0.113}, \quad \bar{d} = d_0(1 - X) + Xd \tag{11}$$

Comparison of the calculated results of grain size of DRX and the experimental results is shown in Fig.5, and the relative errors are less than 11.8%. It presents that the dynamics and kinematics models can be used to describe the law of microstructure evolution of AZ80 magnesium alloy under the condition of a deformation temperature of 533~683 K and the strain rate of 0.001~10 s^{-1}.

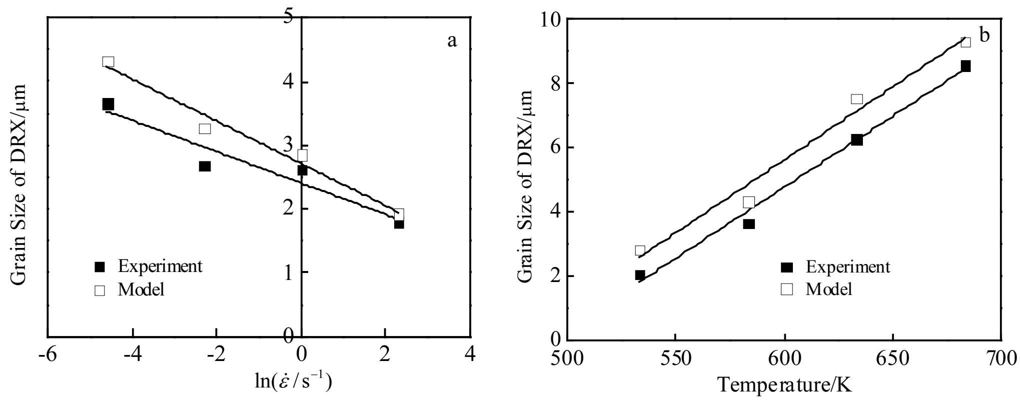

Fig.5 Comparison of the calculated and experimental results of grain size of DRX at a deformation temperature of 583 K (a) and a strain rate of 0.01 s^{-1} (b)

6 Conclusions

1) Energy of thermal activation of AZ80 magnesium alloy is determined, and a kind of constitutive equation of AZ80 magnesium alloy is established.

2) The dynamics model of AZ80 magnesium alloy is established, which is defined as the relationship between the volume fraction of dynamic recrystallized grains, deformation temperature and strain-rate.

3) The kinematics model of AZ80 magnesium alloy is established, which is defined as the relationship between grain size of DRX and function *Z*. The grain size of DRX increases with raising the deformation temperature and reducing the strain rate.

4) Relationship between the critical strain, the steady strain of DRX, and the function *Z* is obtained.

5) The calculated results of grain size of DRX are in agreement with experimental results, and relative errors are less than 11.8%.

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AZ80 镁合金热变形过程中的动态再结晶动力学和运动学模型

王忠堂，江吉浩，刘旭南，于晓林

(沈阳理工大学，辽宁 沈阳 110159)

摘　要：采用热模拟实验方法测试了 AZ80 镁合金的真实应力-应变曲线，变形温度范围为 533~ 683 K，应变速率范围为 0.001~10 s^{-1}，变形程度为 50%。动态再结晶的晶粒尺寸随着变形温度的升高和应变速率的降低而增大。确定了 AZ80 镁合金的热激活能以及 AZ80 镁合金热变形时的本构方程。根据 Sellars 方程，确定了 AZ80 镁合金的动力学模型，其定义为发生动态再结晶体积分数与变形温度和应变速率的函数关系。确定了 AZ80 镁合金的运动学模型，其定义为动态再结晶晶粒尺寸与函数 *Z* 之间的数学关系。动态再结晶晶粒尺寸的模型计算结果与实验结果相吻合，相对误差小于 11.8%。确定了临界应变和稳态应变与函数 *Z* 之间的数学关系。

关键词：镁合金；AZ80；动态再结晶；动力学模型；运动学模型

作者简介：王忠堂，男，1962 年生，博士，教授，沈阳理工大学材料科学与工程学院，辽宁 沈阳 110159，电话：024-24680841，E-mail: ztwang@imr.ac.cn