Materials Science and Engineering A 529 (2011) 300–310

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

A new kinetics model of dynamic recrystallization for magnesium alloy AZ31B

J. Liu [a,*], Z. Cui [a], L. Ruan [b]

[a] National Die & Mold CAD Engineering Research Center, Shanghai Jiao Tong University, Shanghai, China
[b] Department of Mechanical Engineering, Kumamoto University, Kumamoto, Japan

ARTICLE INFO

Article history:
Received 13 February 2011
Received in revised form 1 August 2011
Accepted 9 September 2011
Available online 16 September 2011

Keywords:
Dynamic recrystallization (DRX)
Kinetics model
Strain softening
Magnesium alloy AZ31B

ABSTRACT

The classical kinetics models of dynamic recrystallization (DRX) in the form of Avrami function describe the development of DRX process to a large extent; however, because of the characteristics of exponent function, the conventional models cannot exactly exhibit the development speed of DRX process. Based on this analysis, a new kinetics model of DRX was proposed, which represents the 'slow–rapid–slow' property of DRX development. According to the new model, the development process of DRX can be divided into three phases: slow-beginning phase, rapid-increasing phase and slow-rising-to-balance phase. Because the turning point between the second phase and the third one corresponds to the inflexion from the faster velocity of DRX development to the slower one, the strain at this moment can be considered as the most appropriate and economic strain that guarantees fine grains and saves energy consumption. Take a typical metal characterized by DRX magnesium alloy AZ31B for instance, the Gleeble-1500 thermomechanical simulation compression tests were conducted together with microscopic examination, according to which the model parameters were determined. Statistics shows that the experimental results are in good agreement with the predicted values, which validates the accuracy of the new kinetics model.

1. Introduction

The objective of metal forming is not only to form desired shapes and dimensions, but to obtain superior mechanical properties as well. The in-depth study on microstructural evolutions of hot deformation will be helpful to determine the optimal process parameters of hot working. Dynamic recrystallization (DRX) is considered as one of the most important microstructural evolution mechanisms, which is beneficial to obtain fine metallurgical structures, eliminate defects and improve mechanical properties of products. With the development of computer technologies and numerical simulations, it is crucial to model the microstructural evolutions and predict the microstructural changes. In the last three decades, many researchers have proposed some microstructural evolution models suitable for different materials. Although the DRX kinetics models proposed by researchers have some differences in parameters and forms, they are all based on the Avrami function. By analyzing several typical and highly influential models, a new DRX kinetics model, which is able to more reasonably demonstrate the velocity of DRX was built. The new DRX kinetics model is in accord with the usual way that DRX develops, and has fewer parameters. Through the new model the most favorite and economic strain corresponding to fine and uniform grains is able to be obtained at a given temperature and strain rate, which is significant to design and optimize hot deformation processes.

2. Reviews and discussions

Sellars and co-workers [1,2] conducted pioneering research on microstructural evolution on the basis of a great quantity of Gleeble thermomechanical tests, and a series of models which cover almost all the probable physical metallurgical phenomena related to DRX, static recrystallization (SRX) and grain growth were put forward. The DRX kinetics model proposed by Sellars based on Avrami function is as follows:

$$X_{DRX} = 1 - \exp\left(-0.693\left(\frac{t}{t_{0.5}}\right)\right) \quad (1)$$

where X_{DRX} is the dynamically recrystallized volume fraction, $t_{0.5}$ is the time for 50% DRX, t is the time for X_{DRX} to occur. In Sellars' model, the using of the constant 0.693 is crucial and very skillful, which make all the parameters have obvious physical meanings. Later, some researchers such as McQueen et al. [3] published DRX kinetics models where the dynamically recrystallized volume fraction are also formulated in the form of time function.

* Corresponding author. Tel.: +86 21 62813430; fax: +86 21 62827605.
E-mail addresses: liujuan@sjtu.edu.cn, j.liu.china@gmail.com (J. Liu).

0921-5093/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2011.09.032

Yada et al. [4] built the following DRX kinetics model of plain C–Mn steel in the form of strain function:

$$\begin{cases} X_{\mathrm{DRX}} = 1 - \exp\left(-0.693\left(\dfrac{\varepsilon-\varepsilon_c}{\varepsilon_{0.5}}\right)^2\right) \\ \varepsilon_{0.5} = 1.144\times10^{-3} d_0^{0.28}\dot{\varepsilon}^{0.05}\exp\left(\dfrac{6420}{T}\right) \end{cases} \tag{2}$$

where ε_c is the critical strain, $\varepsilon_{0.5}$ is the strain for 50% DRX, d_0 is the initial grain size, T is the deformation temperature, $\dot{\varepsilon}$ is the strain rate. Although the different variables, in comparison to those in Sellars' model, are used in Yada's model, *i.e.*, Sellars' model is the function of time and Yada's model is the function of strain, both of them are same in nature. It is because that the function of time is consistent with the function of strain when the stain rate is a constant. So, Yada's model can be applied to unsteady numerical simulations during hot deformations as the result of the using of the strain form. Thus, many kinds of commercial FEM softwares, such as Marc, Superform and Deform employ Yada's model to predict microstructural evolution. Different from Sellars' model, the physical meaning of the variable of $\varepsilon_{0.5}$ in Yada model is not obvious, which does not precisely represent the strain for 50% DRX any more, but a statistic. So, it is difficult to determine the value of $\varepsilon_{0.5}$. Apart from this, the difference between Sellars' model and Yada's model is that the exponent used in Sellars' model is 1, but in Yada's model 2.

In recent years Kim and co-workers [5,6], developed the following DRX kinetics model in the form of modified Avrami equation based on the thermomechanical simulation tests, the equation is as follows:

$$\begin{cases} X_{\mathrm{DRX}} = 1 - \exp\left(-\left(\dfrac{\varepsilon-\varepsilon_c}{\varepsilon^*}\right)^{m'}\right) \\ m' = 1.12\left(\dfrac{Z}{A}\right)^{-0.08} \end{cases} \tag{3}$$

where ε^* is the strain for maximum softening rate, Z is the temperature-compensated strain rate, *i.e.* the Zener–Hollomon parameter, A is a material constant. In Kim's model, the strain for maximum softening rate—ε^* is used instead of the strain for 50% DRX $\varepsilon_{0.5}$ of Yada's model. According to the classic theory, the development process of DRX is similar to that of phase transition. The velocity of DRX begins from zero and slowly increases, and after a latent period the velocity of DRX starts to rapidly increase, and after it reaches the maximum the velocity of DRX gradually decreases, in the end the velocity of DRX is close to zero. Since ε^* represents the strain for maximum softening rate, *i.e.*, the strain for maximum velocity of DRX, ε^* in Kim's model physically coincides with $\varepsilon_{0.5}$ (the strain for 50% DRX) in Yada's model. The constant 0.693, however, is not used in Kim's model and the component m' is described as the function of Z through regression analysis. Compared with Sellars' model, the parameters in Kim's model do not have the obvious physical meanings, but just statistic meanings.

Kopp and co-workers [7,8] put forward the following DRX kinetics model in the form of strain function:

$$\begin{cases} X_{\mathrm{DRX}} = 1 - \exp\left(-k_d\left(\dfrac{\varepsilon-\varepsilon_c}{\varepsilon_{0.5}-\varepsilon_c}\right)\right) \\ \varepsilon_{0.5} = k_1 Z^{n_1} \end{cases} \tag{4}$$

where ε_c is the critical strain, $\varepsilon_{0.5}$ is the strain for 50% DRX, k_d, k_1 and n_1 are material constants. Kopp did not assign the favorite value to k_d. By analyzing it is able to be found that the variables in Kopp's model have obvious physical meanings when k_d is equal to 0.693. Similar with Sellars' model, the exponent in Kopp's model equals 1.

Laasraoui and Jonas [9], Serajzadeh and Taheri [10] made great efforts to build the DRX kinetics models suitable for different kinds of steel, the equations can be generalized as the following form:

$$X_{\mathrm{DRX}} = 1 - \exp\left(-k_d\left(\frac{\varepsilon-\varepsilon_c}{\varepsilon_p}\right)^{n_d}\right) \tag{5}$$

where ε_p is the peak strain, ε_c is the critical strain, k_d and n_d are material constants. In Eq. (5) $\varepsilon_{0.5}$ is substituted by ε_p in contrast to Yada model. As far as k_d and n_d was concerned, some researchers think that they are the function of Zener–Hollomon parameter or the function of $\dot{\varepsilon}$ and T, but other researchers think that they are constants under different deformation conditions. Recently, Eq. (5) is often used as the general form of the DRX kinetics model.

By analysis, it can be found that all the above typical kinetics models of DRX are based on Avrami function and the differences among them are the choices of the constants and the exponents and the using of $\varepsilon_{0.5}$, ε^* and ε_p in the models. Synthetically considering Sellars' model, Kopp's model, Yada's model and the general form Eq. (5), the following modified Kopp's model is used to discuss the classical DRX kinetics models based on Avrami form.

$$X_{\mathrm{DRX}} = 1 - \exp\left(-0.693\left(\frac{\varepsilon-\varepsilon_c}{\varepsilon_{0.5}-\varepsilon_c}\right)^{n_d}\right) \tag{6}$$

where ε_c is the critical strain, $\varepsilon_{0.5}$ is the strain for 50% DRX, and n_d is a material constant. The using of 0.693 in Eq. (6) makes all the variables in model have obvious physical meanings. As the values of the exponent n_d used in Sellars' model, Yada's model and Eq. (5) are different; the influence of different n_d values on the DRX kinetics models based on Avrami form is able to be investigated by analyzing the modified Kopp's models with different n_d values. So, as a typical example of the classical DRX kinetics models, the modified Kopp's model Eq. (6) is discussed in the next section.

3. A new kinetics model of DRX

The characteristics of DRX are as follows: the dynamically recrystallized volume fraction equals zero when the strain is smaller than the critical strain, and the maximum of the dynamically recrystallized volume fraction equals 1; once the strain exceeds the critical strain, the dynamically recrystallized volume fraction first slowly increases, and then rapidly increases, at last slowly increases. Based on these characteristics of DRX process and the feature of the limit of exponent function, the following new kinetics model of DRX was proposed.

$$X_{\mathrm{DRX}} = [1 + k_v^{(1-(\varepsilon-\varepsilon_c/\varepsilon_{0.5}-\varepsilon_c))}]^{-1} \tag{7}$$

where ε_c is the critical strain; $\varepsilon_{0.5}$ is the strain for 50% DRX; k_v is a constant related to the velocity of DRX, which is mainly decided by the initial grain size and the stacking-fault energy.

Take ε_c of 0.2 and $\varepsilon_{0.5}$ of 0.5 for example, the curves of DRX kinetics based on the modified Kopp's model at different values of n_d by Eq. (6) are shown in Fig. 1(a). Take ε_c of 0.2 for example, the curves of DRX kinetics based on the new kinetics model by Eq. (7) at different values of k_v and $\varepsilon_{0.5}$ are shown in Fig. 1(b).

It can be found from Fig. 1(a) that when the strain exceeds the critical strain ε_c, the kinetics curves of DRX based on the modified Kopp's model exhibit different rising trends with increasing strain at different values of n_d. Moreover, the dynamically recrystallized volume fraction is greater than zero when the strain is less than the critical strain ε_c and the value of n_d is equal to even numbers 2 and 4; the dynamically recrystallized volume fraction is less than zero when the strain is less than the critical strain ε_c and the value of n_d is equal to odd numbers 1 and 3. It is inconsistent with the rule of DRX process and it is caused by the features of exponential function. Fig. 1(b) shows that the new kinetics model of DRX is consistent with the rule of DRX. By analyzing Eq. (7), it is able to be