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Mathematical models for predicting the austenite grain size in hot working of GCr15 steel

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A B S T R A C T

The objective of this study is to develop a set of mathematical models which can predict the austenite grain size of GCr15 steel in hot working process. The models can describe the evolution of grain size during dynamic recrystallization (DRX), metadynamic recrystallization (MDRX), static recrystallization (SRX), and grain growth process after recrystallization, respectively. The DRX behavior in GCr15 steel was investigated by the single hot compression tests, and the double compression tests with different inter-stage delay times were used to research the kinetics of MDRX and SRX. The tests were performed on the Gleeble-3800 thermo-mechanical simulation machine at temperature from 950 to 1150 °C, strain rate from 0.01 to 50 s^{-1} and initial austenite grain size from 26.3 to 90.0 μm. In addition, a set of specimens were heated to 950, 1050, 1100 and 1150 °C for 0–480 s to determine the grain growth model after recrystallization. The predicted results of grain size are in good agreement with the measured ones.

1. Introduction

The thermo-mechanical processing of metals at high temperature involves a number of microstructural changes, such as dynamic recrystallization (DRX), metadynamic recrystallization (MDRX), static recrystallization (SRX) and grain growth. The microstructure evolution has an important influence on the mechanical properties of material. In order to improve the quality and productivity of metal products, it is necessary to predict and control the microstructure of the final products. However, it is very difficult to analyze hot working process by experimental method because all variables vary with the deformation history [1]. Recently, the modeling of microstructure evolution in hot working has received tremendous attention [2–7].

As the pioneers of computer simulation on microstructure evolution, Sellars and his co-workers [8–10] suggested a set of mathematical models to analyze the microstructure evolution of carbon steel in hot rolling several decades ago. Since then some empirical models for the prediction of microstructure evolution have been developed [11–18]. For example, Yada and Senuma [16,17] proposed an empirical equation to analyze the microstructure evolution of carbon steel with less than 1%Mn. Cho [18] developed a set of models to predict the DRX, SRX and grain growth phenomena in die steel during thermo-mechanical processing. Based on the models reported by other researchers, many researchers have taken their attention on predicting microstructure evolution of different steels in hot deformation. Jang [1] developed an analysis program, which combined Yada's empirical equations with the rigid-thermoviscoplastic finite element method, to investigate the microstructure evolution during a hot forging process with large deformation. The simulation results were in good agreement with those of experiment. Grass [19] predicted the evolution of austenite grain size during a five-pass stretch rolling on the basis of the recrystallization models established by Kuziak and other researchers. The calculated grain sizes were compared with those of formed components. As a result, the good agreement was shown. Despite the fact that these predicted results based on the recrystallization models for other steels are in good agreement with the experimental ones, the recrystallization kinetics of the steels which have not been researched needs to be further investigated.

This work aims at investigating the recrystallization and grain growth behavior of GCr15 steel by hot compression and annealing tests on the Gleeble-3800 thermo-mechanical simulation machine. In accordance with the experimental results, the effect of

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temperature, strain rate and initial grain size on the kinetics of DRX, MDRX and SRX was discussed, and a set of mathematical models which can predict the evolution of austenite grain size in hot working of GCr15 steel were obtained. Comparisons between measured and predicted results of grain size were conducted.

2. Experiments

2.1. Materials, specimens and experimental equipment

In the present study, a typical GCr15 steel provided in the form of bar with the diameter of 15 mm by Dongbei Special Steel Group is employed, and the chemical composition is 0.99%C, 0.24%Si, 0.31%Mn, 0.01%P, 0.003%S, 1.44%Cr, 0.05%Ni, 0.12%Cu, 0.02%Mo and the balance Fe. Before the experiment, the cylindrical specimens with the diameter of 8 mm and with the length of 12 mm were machined from the hot rolled bar. All tests were performed on a computer-controlled, servo-hydraulic Gleeble-3800 thermo-mechanical simulation machine.

2.2. Experimental procedure

The single hot compression tests were used to study the DRX behavior of GCr15 steel. All specimens were heated to 1150 °C at the heating rate of 5 °C/s, and held for 2, 5 and 8 min at 1150 °C to produce initial austenite grain sizes 26.3, 52.6 and 90.0 μm, respectively. Then, they were cooled down to deformation temperatures 950, 1000, 1050, 1100 and 1150 °C, and deformed at strain rates 0.01, 0.1, 1, 5 and 10 s^{-1}. The specimens were quenched in water after tests immediately. The stress–strain curves under different deformation conditions were measured during deformation.

The MDRX and SRX behavior of GCr15 steel was investigated by the double hot compression tests. The initial austenite grain size, deformation temperature and strain rate were the same as the ones in the single hot compression tests. The only difference was that the deformation in the double tests was divided into two parts, and there was an inter-stage delay time of 1–100 s between first and second deformation to enable MDRX and SRX to progress.

When the recrystallization is complete, new structure is metastabled, so austenite grains will grow to reduce the grain boundary energy per unit volume. In order to investigate the growth behavior of austenite grain in the tested steel, the annealing tests were performed. The austenitize temperatures were 950, 1050, 1100 and 1150 °C, and the holding time varied from 0 to 480 s.

3. Results and discussion

3.1. The flow stress

The flow stress has a significant effect on the deformation force and the flow behavior of metals. It is strongly influenced by the deformation temperature, strain rate and initial grain size.

Fig. 1a shows the influence of deformation temperature on stress–strain curves. The curves indicate that the tested steel exhibits a typical DRX behavior under different temperatures from 950 to 1150 °C when the initial austenite grain size is 90 μm and strain rate is 0.1 s^{-1}. The flow stress increases to a peak value which is followed by a strain softening and a steady state. The peak stress and peak strain decrease with increasing temperature. The decrease indicates that higher deformation temperature can promote the DRX behavior of GCr15 steel.

Fig. 1b shows the stress–strain curves obtained for the tested steel deformed at 1050 °C and different strain rates 0.01, 0.1 and 1 s^{-1}. The curves are similar to the ones in Fig. 1a, and exhibit the typical DRX behavior too. While on the curves deformed at 1050 °C and strain rates 5 and 10 s^{-1}, there is a steady region where the stress does not change obviously at a wide strain range after the peak stress. The phenomenon makes out that higher strain rate can block the start of DRX in the tested steel.

The dependence of flow stress on initial austenite grain size is presented in Fig. 1c. It can be seen that for initial austenite grain sizes 26.3, 52.6 and 90.0 μm, the value of peak stress remains almost constant only if deformation temperature and strain rate are identical. It is in accordance with the results of other steels [20,21]. However, the initial austenite grain size has a pronounced effect on peak strain and steady stress. An increase in initial grain size is accompanied by a rise in peak strain and steady stress.

Typical stress–strain curve obtained from the double hot compression test of GCr15 steel is depicted in Fig. 1d. A test specimen is loaded at a constant strain rate 0.1 s^{-1} up to the pre-strain 0.13 and then unloaded. After an inter-stage delay time 3 s, the test specimen is reloaded at the same strain rate. The flow stress increases faster during the second compression than during the first one. It indicates that the recrystallization did not finish before the second deformation.

3.2. Critical strain for the onset of dynamic recrystallization

DRX is of interest because it softens metals and affects their final mechanical properties. At the same time, DRX also affects post deformation softening. As soon as DRX is initiated, MDRX will occur between stands. However, if DRX does not occur during deformation, SRX will take place and will play an important role in the flow stress and microstructure evolution of the material. So, the critical strain for the onset of DRX is an important parameter, and it is necessary to investigate the critical strain under different deformation conditions.

DRX critical strain can be approximately determined by peak strain [20]. Researchers have found that the following relationship between the critical strain and the peak strain works very well for most steels [22]:

$$\varepsilon_c = 0.83 \cdot \varepsilon_p \tag{1}$$

where ε_c is the critical strain, ε_p is the peak strain.

As shown in the stress–strain curves of the steel, the value of peak strain depends on the initial grain size, deformation temperature and strain rate. Many formulas [20,23,24] have been proposed to describe the relationship between peak strain and deformation conditions. By employing the formula mentioned in [23], the peak strain for the tested steel was determined as follows:

$$\varepsilon_p = 4.28 \times 10^{-3} d_0^{0.22} \dot{\varepsilon}^{0.19} \exp\left(\frac{4461.0}{T}\right) \tag{2}$$

where d_0 is the initial grain size, $\dot{\varepsilon}$ is the strain rate, T is the absolute temperature.

3.3. The kinetics of recrystallization

Due to the difficulty in modeling accurately the recrystallization process theoretically, researchers have resorted to empirical techniques. The recrystallized fraction at a given instant is a function of the time for 50% recrystallization, and is generally given by the following Avrami equation [25–30]:

$$X = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^2\right] \tag{3}$$

where X is the recrystallized fraction, t is the deformation time after the critical strain for DRX and the delay time after deformation for MDRX and SRX, $t_{0.5}$ equals to t for 50% recrystallization.