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Materials

Research on microstructural evolution and dynamic recrystallization behavior of JB800 bainitic steel by FEM

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Abstract: Single pass compression tests were conducted on Gleeble1500 thermal simulator. The effect of different deformation parameters on the grain size of dynamically recrystallized austenite was analyzed. A mathematical model of dynamic recrystallization and a material database of JB800 steel, whose tensile strength is above 800 MPa, were set up. A subprogram was compiled using Fortran language and called by Marc finite element software. A thermal coupled elastoplastic finite element model was established to simulate the compression process. The grain size of recrystallized austenite obtained by different recrystallization models was simulated. The results show that the optimized dynamic recrystallization model of JB800 bainitic steel has a higher precision and yields good agreement with metallographic observations.

Key words: high strength bainitic steel; dynamic recrystallization; microstructural evolution; finite element method

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1. Introduction

With the rapid development of national economy in China, demand for medium and heavy steel plates with high strength and toughness has been rising. Therefore, researchers of domestic steel enterprises and scientific research institutions pay much attention for the development of such steel products. The development of bainitic steel with excellent integrated mechanical properties is one of the major research interests. Grain boundary allotriomorphic ferrite/granular bainite steel developed by Professor Fang of Tsinghua University is the representative of such steels [1].

In the steels containing microalloyed elements, such as Cr, high temperature deformation behavior of austenite was generally intricate. However, the behavior of austenite recrystallization during hot rolling process has much influence on the microstructure and properties of products. Thus, the study on the rules of high-temperature dynamic recrystallization (DRX) is very important to establish rational rolling technology for the production of plates with excellent integrated properties. The effect of deformation parameters on the austenite dynamic recrystallization was analyzed to set up a recrystallization model. The distribution of grain size during compression process was also simulated, which makes the visualization of microstructural evolution. The influence of different recrystallization models on the austenite grain size was simulated and compared.

2. Materials and experimental procedures

2.1. Materials

The used material in this experiment was JB800 plate obtained from practical production. Its chemical composition and mechanical properties are listed in Tables 1 and 2, respectively.

Table 1. Chemical composition of the test steel wt %

C	Si	Mn	P	S	V, Cr
0.100	0.820	2.140	0.012	0.001	Bal.

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Table 2. Mechanical properties of the test steel

σ_s / MPa	σ_b / MPa	δ_5 / %	Ballistic work / J
560	860	17	45

2.2. Experimental procedures

Cylindrical compression specimens with 15 mm in gage length (*L*) and 8 mm in gage diameter (*d*) were machined. Single pass hot compression tests were carried out on a Gleeble1500 thermal simulator. The specimens were reheated up to 1473 K at 10 K/s and held for 3 min, then cooled down to different deformation temperatures of 1273 K, 1323 K, 1373 K, and 1423 K, respectively. The samples were deformed with a true strain of 0.63 at different strain rates of 0.01 s^{-1}, 0.05 s^{-1}, 0.1 s^{-1}, and 0.3 s^{-1}, respectively, followed by water quenching to observe the austenite microstructure. The stress and strain were acquired simultaneously.

To measure the austenite grain size, the specimens were sectioned along the radial direction, then ground and polished using diamond paste. For revealing the microstructure, the specimens were etched with a thermal saturated aqueous solution of picric acid and some teepol. The solution was heated in the temperature range of 60-80°C and the etching time was about 3-5 min. The optical microstructure in the center and edge of the section plane was observed using a Leca Dmrxp microscope. The austenite grain size was measured using the mean linear intercept method.

3. Results and discussion

3.1 Curves of stress to strain

Fig. 1 shows the stress-strain curves of the JB800 bainitic steel deformed at various temperatures *T* and strain rates $\dot{\varepsilon}$. The flow curves indicate that the JB800 bainitic steel exhibits a typical DRX behavior under the condition of higher temperatures and lower strain rates. The stress rises to the first peak followed by softening toward a steady state region, and then the stress increases with the increase in strain because of strain hardening. The values of critical stress and critical strain of dynamic recrystallization increase with the decrease of deformation temperature at the same stain rate. While under the condition of the same temperature, the values of critical stress and critical strain of DRX increase with the increase in stain rate. As illustrated in Fig. 1, dynamic recrystallization can occur under different deformation parameters described in this article.

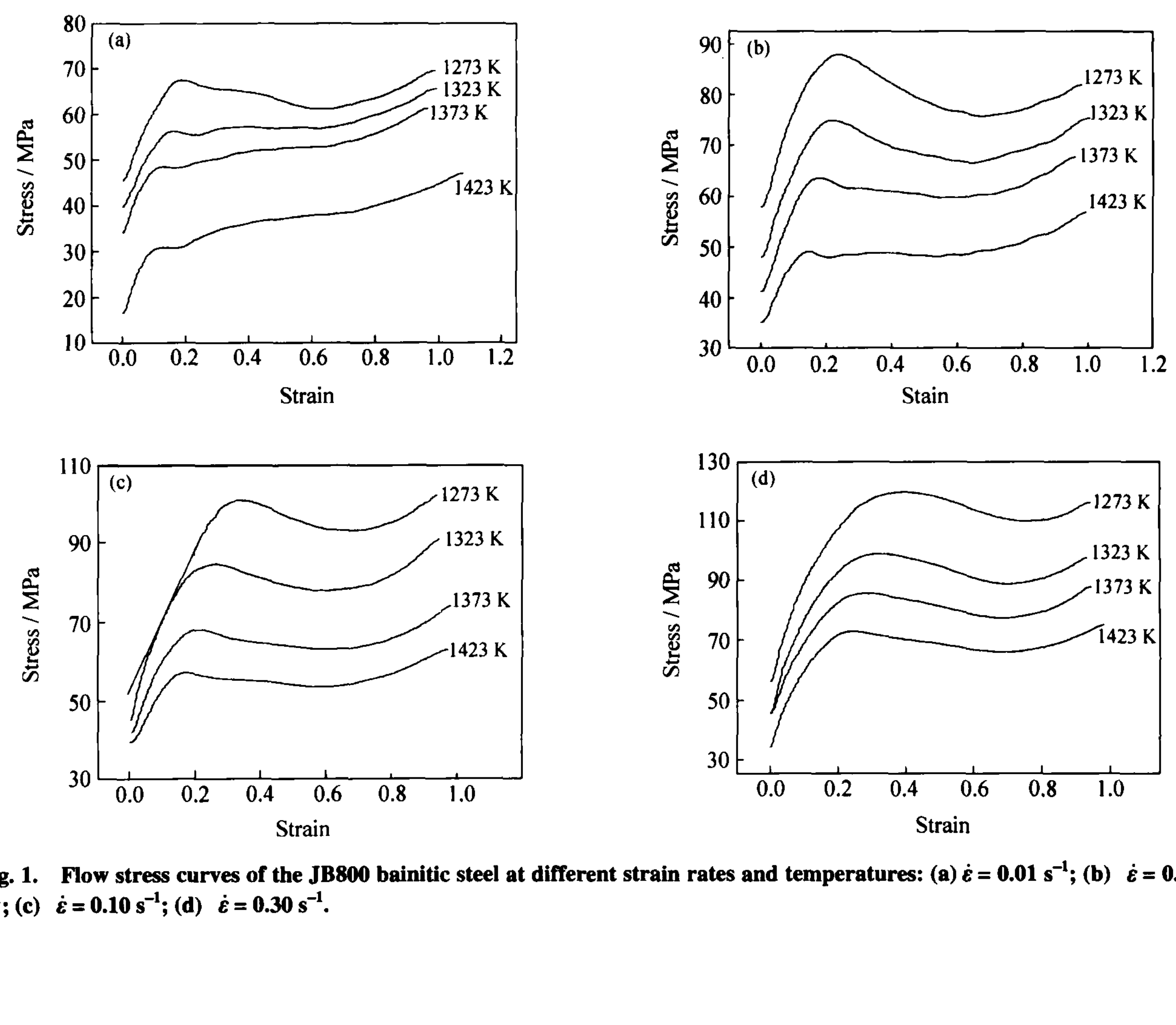

Fig. 1. Flow stress curves of the JB800 bainitic steel at different strain rates and temperatures: (a) $\dot{\varepsilon}$ = 0.01 s^{-1}; (b) $\dot{\varepsilon}$ = 0.05 s^{-1}; (c) $\dot{\varepsilon}$ = 0.10 s^{-1}; (d) $\dot{\varepsilon}$ = 0.30 s^{-1}.

3.2. Dynamic recrystallization models

3.2.1. DRX model developed by Hodgson [2-3]

(1) Correlative parameters.

$$\varepsilon_c = 5.6\times10^{-4}\cdot d_0^{0.3}\cdot Z^{0.17} \quad (1)$$

$$Z = \dot{\varepsilon}\cdot\exp\left(\frac{Q}{RT}\right) \quad (2)$$

where ε_c is the critical stain of dynamic recrystallization; d_0, the initial austenitic grain size, μm; Z, the Zener-Hollomon parameter; $\dot{\varepsilon}$, the strain rate, s^{-1}; Q the activation energy, J/mol; R, gas constant, 8.314 $J\cdot mol^{-1}K^{-1}$; T, thermodynamic temperature, K.

(2) DRX grain size.

$$d_{DRX} = 1.6\times10^4\cdot Z^{-0.23} \quad (3)$$

(3) Equation of austenite DRX fraction.

$$x_{DRX} = 1-\exp\left[-0.693\cdot\left(\frac{t}{t_{0.5}}\right)^{1.5}\right] \quad (4)$$

$$t_{0.5} = 0.4\times Z^{-0.8}\cdot\exp\left(\frac{240000}{RT}\right) \quad (5)$$

where x_{DRX} is the DRX fraction; t, the time, s; $t_{0.5}$, the time for 50% recrystallization, s.

3.2.2. DRX model developed by Yada [4]

(1) Correlative parameters.

$$Z = \dot{\varepsilon}\exp\left(\frac{267100}{RT}\right) \quad (6)$$

$$\varepsilon_c = 4.76\times10^{-4}\exp\left(\frac{8000}{T}\right) \quad (7)$$

(2) Austenite DRX fraction equation.

$$x_{DRX} = 1-\exp\left[-0.693\left(\frac{\varepsilon-\varepsilon_c}{\varepsilon_{0.5}}\right)^2\right] \quad (8)$$

$$\varepsilon_{0.5} = 1.144\times10^{-12}\cdot d_0^{0.28}\cdot\varepsilon^{0.05}\exp\left(\frac{6420}{T}\right) \quad (9)$$

Here $\varepsilon_{0.5}$ is the strain for 50% recrystallization.

(3) DRX grain size.

$$d_{DRX} = 22600\cdot Z^{-0.27} \quad (10)$$

3.2.3. DRX model developed

(1) Peak stress and strain equation.

Various empirical Eqs. (11) and (12) have been proposed to describe the Zener-Hollomon parameter [5-8].

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \quad (11)$$

$$Z = A_1\sigma_p^n \quad (12)$$

where A_1 is a material-dependent constant, n is a temperature-independent constant, and σ_p is the peak stress. Combining Eqs. (11) and (12):

$$A_1\sigma_p^n = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \quad (13)$$

Taking logarithm of Eq. (13), the following equation can be obtained:

$$\ln A_1 + n\ln\sigma_p = \ln\dot{\varepsilon} + \frac{Q}{RT} \quad (14)$$

The slope of the line $\ln\sigma_p - \ln\dot{\varepsilon}$ is $1/n$ and that of the line $\ln\sigma_p - 1/T$ is Q/Rn.

By regressing the experimental data as shown in Fig. 1, the results can be obtained as Q_{def} = 299.5 kJ/mol, n = 5.053, and A_1 = 12.74. Q_{def} is the activation energy of deformation.

The Zener-hollomon parameter of the JB800 bainitic steel can be described as follow:

$$Z = \dot{\varepsilon}\exp\left(\frac{299500}{RT}\right) \quad (15)$$

$$Z = 12.74\cdot\sigma_p^{5.053} \quad (16)$$

So the peak stress equation can be written as

$$\sigma_p = 0.62\cdot Z^{0.20} \quad (17)$$

The peak strain depends on the Zener-Hollomon parameter Z according to Eq. (18) [9-10]

$$\varepsilon_p = UZ^W \quad (18)$$

Taking the logarithm of Eq. (18), the following equation can be obtained:

$$\ln\varepsilon_p = \ln U + W\ln Z \quad (19)$$

where U and W are material constants, ε_p is the peak strain. The experimental data is regressed as shown in Fig. 1 according to Eq. (19), the peak strain equation of the JB800 steel follows as

$$\varepsilon_p = 1.52\times10^{-3}\cdot Z^{0.205} \quad (20)$$

(2) DRX grain size.

The previous study about DRX showed that strain softening and hardening reached to balance induced by dynamic recrystallization and dynamic recover when the deformation attained to steady-state flow strain. After this, the grain size of dynamic recrystallization did not change with strain and have no relationship with the initial grain size. The equation of the grain size of dynamic recrystallization to the

Zener-Hollomon parameter were deduced [11-12]:

$$d_{\mathrm{DRX}} = aZ^{b} \tag{21}$$

where a and b are constants, Z is the Zener-Hollomon parameter. Taking the logarithm of Eq. (21), the following equation can be obtained:

$$\ln d_{\mathrm{DRX}} = \ln a + b \ln Z \tag{22}$$

After the quenched specimens were etched, the recrystallized grain size was measured using an optical microscope. The initial austenite grain size is 120 μm. The DRX grain sizes at different deformed parameters are summarized in Table 3.

Table 3. Measured austenite grain sizes **μm**

Temperature / K	Strain rate / s^{-1}		
	0.01	0.1	0.3
1273	36	28	21
1373	48	38	30

As shown in Table 3, the DRX grain size decreased with the increase in stain rate and the decrease in temperature. The data was regressed and the DRX grain size equation can be obtained:

$$d_{\mathrm{DRX}} = 1.735\times10^{3} \cdot Z^{-0.161} \tag{23}$$

4. Simulation of single pass compression process by FEM

4.1. Finite element model

The compression process of specimens on a Gleeble1500 thermal simulator was simulated by elastoplastic FEM to investigate the dynamic recrystallization behavior and the microstructural evolution rules. Thermal-mechanical coupled analysis between the models of elastoplastic finite element and microstructural evolution has been performed to analyze the state of dynamic recrystallization during deformation. The finite element model presented in Fig. 2 shows that AB and CD were rigid edge and EF was the axisymmetric centerline of specimens. The cylindrical specimens were 15 mm in height and 8 mm in diameter. The specimens were compressed at 1273 K at a strain rate of 0.05 s^{-1}. A material database was set up based on experimental data. Fortran language compiling Marc user subprogram was applied, the dynamic recrystallization behavior and microstructural evolution of the JB800 bainitic steel were simulated by using the Hodgson recrystallization model, Yada model, and optimized recrystallized model of the JB800 bainitic steel, respectively.

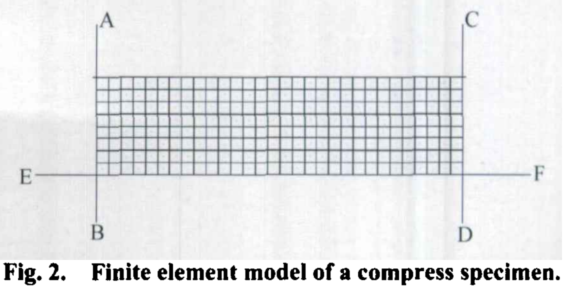

Fig. 2. Finite element model of a compress specimen.

4.2. Results of simulation

The results of simulation are shown in Fig. 3, which reveals the austenitic grain size distribution of the deformed specimen using different microstructural evolution models. From Fig. 3, it can be seen that there are fine grains at the center of specimens where the degree of deformation is more severe. Fig. 3(a) shows the simulating result using the Hodgson model, which shows the austenitic grain size at the center of specimens is 38 μm, while 48.3 μm at the edge. Fig. 3(b) shows the simulating result using the Yada model, which shows the grain sizes at the center and edge of specimens are 18.7 μm and 24.8 μm, respectively. Fig. 3(c) shows the simulating result using the model described in this article, which shows the grain sizes at the center and edge of specimens are 25.3 μm and 29.8 μm, respectively.

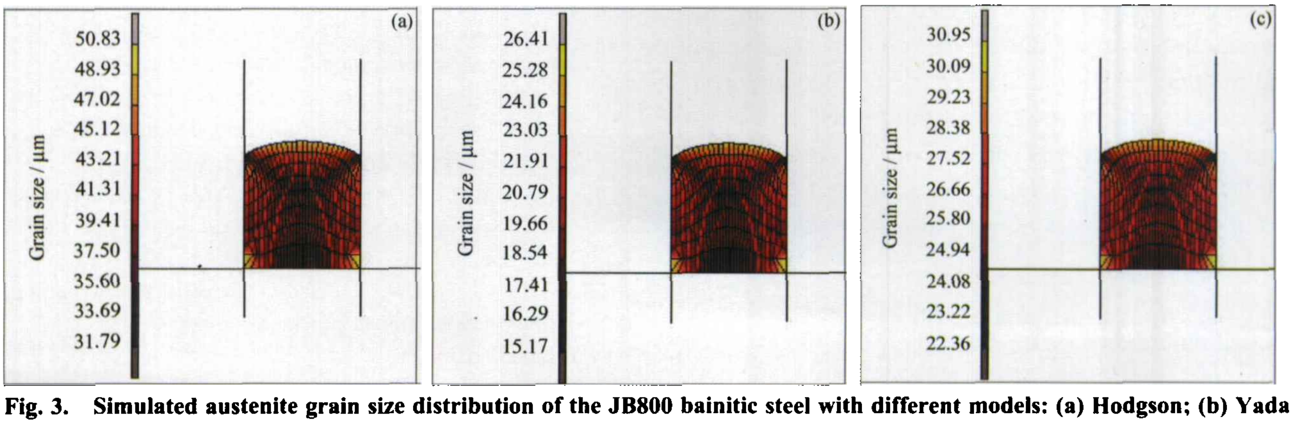

Fig. 3. Simulated austenite grain size distribution of the JB800 bainitic steel with different models: (a) Hodgson; (b) Yada; (c) new model.

Fig. 4 shows the microstructures of the JB800 bainitic steel deformed by the thermal simulator at 1273 K and a strain rate of 0.05 s^{-1}. It can be seen that the measured grain sizes at the center and edge of the specimen are 24.5 μm and 29 μm, respectively. Complete dynamic recrystallization takes place during deformation and there is fine microstructure at the center of the specimen as shown in Fig. 4. The plastic stain and stain rate at the edge of the specimen are less than those at the center, which causes the decrease of the Zener-Hollomon parameter at the edge than at the center, so the grain size at the edge of the specimen is larger than that at the center.

From the forgoing experimental measurement and analysis, it can be seen that the value of austenitic grain size simulated by the optimized dynamic recrystallization model is in well agreement with experimental results.

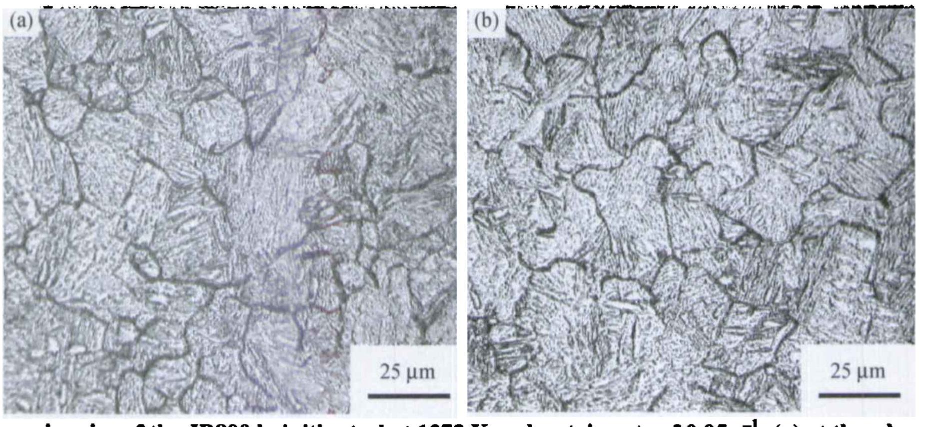

Fig. 4. Austenite grains size of the JB800 bainitic steel at 1273 K and a stain rate of 0.05 s^{-1}: (a) at the edge; (b) at the center.

5. Conclusions

Dynamic recrystallization was investigated in JB800 bainitic steel by testing and FEM simulation. There are many advantages in developing a program combined with the finite element method and the model for predicting microstructural evolution. In this study, experiment and simulation for single pass compression process have been performed to predict the microstructural evolution of the material with different DRX models, and the following conclusions can be drawn.

(1) On the basis of experimental data, a material database and an optimized dynamic recrystallization model of JB800 bainitic steel were obtained.

(2) The single pass compression process of JB800 bainitic steel was simulated and its finite element model was established. To simulate the microstructural evolution with different DRX models, an analysis program has been developed by combining the thermo-elastoplastic finite element model and the microstructural evolution model. By considering heat, mechanics, and microstructure during the process, a coupled simulation was carried out. The results show that the optimized DRX model described in this article was the most consistent with the fact among three models.

(3) Complete dynamic recrystallization takes place during compression process and the value of austenitic grain size at the edge of the specimen is larger than that at the center.

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