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Investigation on Static Softening Behaviors of a Low Carbon Steel Under Ferritic Rolling Condition

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The study aims to postulate a theoretical hypothesis for the finishing period of ferritic rolling technique of the low carbon steel. The static softening behavior during multistage hot deformation of a low carbon steel has been studied by double hot compression tests at 700-800 °C and strain rate of 1 s^{-1} using a Gleeble-3500 simulator. Interrupted deformation is conducted with interpass times varying from 1 to 100 s after achieving a true strain of 0.5 in the first stage. The results indicate that the flow stress value at the second deformation is lower than that at the first one, and the flow stress drops substantially. The static softening effects increase with the increase of deformation temperature, holding temperature, and interpass time. The value of the ferritic static softening activation energy is obtained, and the static softening kinetics is modeled by the Avrami equation.

Keywords ferritic rolling, low carbon steel, static softening

1. Introduction

With the increase of the need for thin- or even ultra-thin-rolled products, steelmakers around the world have recently begun showing an interest in ferritic rolling. With use of this technology, not only the product range can be broadened, but also the cost of hot-rolled strips is decreased (Ref 1-3). The advantages of the ferritic rolling technology are obvious in the production of interstitial-free steel. Compared with traditional austenic hot rolling, the influence of ferritic rolling on metallurgical aspects of the hot deformation in the low carbon is far greater than that in interstitial-free steel due to a change in rolling temperature range. Therefore, many studies on how to apply ferritic rolling technologies into the production of the low carbon steel have been carried out (Ref 4-7). The static softening behavior between passes plays an important role in the hot-deformation processes. However, reports on the ferritic static softening during hot deformation are few. In order to postulate a theoretical hypothesis for the finishing period of the ferritic rolling technique of the low carbon steel, the ferritic static softening behavior during multistage hot deformation of low carbon steel was studied by double hot compression tests by means of a Gleeble-3500 simulator.

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2. Experimental Procedures

The low carbon steel used in this investigation had the following chemical composition: 0.04C, 0.05Si, 0.26Mn, 0.006S, 0.01P (wt.%), balance Fe. A_1 temperature of 843 °C was obtained by way of thermal dilation.

Compression specimens with ∅ 10 mm × 15 mm are machined, and the cylinder axes are parallel to the through-thickness direction of the as-received material.

Fractional softening was determined by means of interrupted axial compression tests, which are carried out using a Gleeble-3500 simulator. The thermomechanical treatment schedule employed is outlined in Fig. 1. All the specimens are heated to 1150 °C quickly and held for 5 min to obtain a uniform microstructure before the hot compression test. Then, they were cooled to the hot compression temperature (700, 750, 800 °C) at a cooling rate of 10 °C/s and held for 2 min. The interrupted deformation steps were conducted with interpass time varying from 1 to 100 s after achieving a true strain of approximately 0.5 in the first stage. Constant strain rate of 1 s^{-1} was adopted in all the tests.

With the use of the offset stress method, the fractional softening (X) was calculated according to the following equation (Ref 8, 9):

$$X = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1} \qquad \text{(Eq 1)}$$

where σ_m is the flow stress immediately before unloading, σ_1 is the initial yield stress, and σ_2 is the yield stress on reloading.

3. Results

3.1 Static Softening Behavior

True stress-strain curves for the tested steel deformed at 800, 750, and 700 °C at a constant strain rate of 1 s^{-1} are shown in

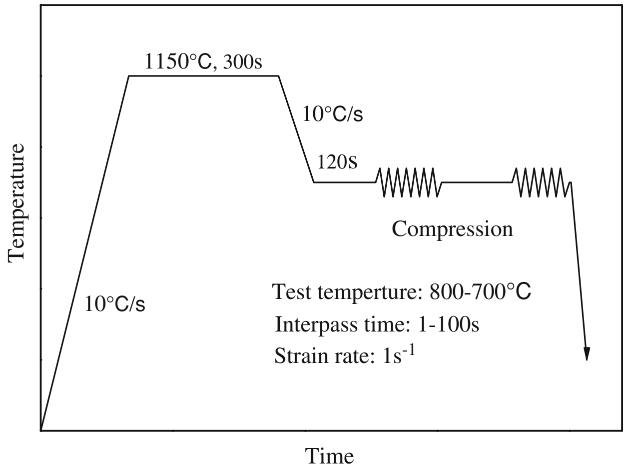

Fig. 1 Schematic diagram of the schedule employed in the double compression tests

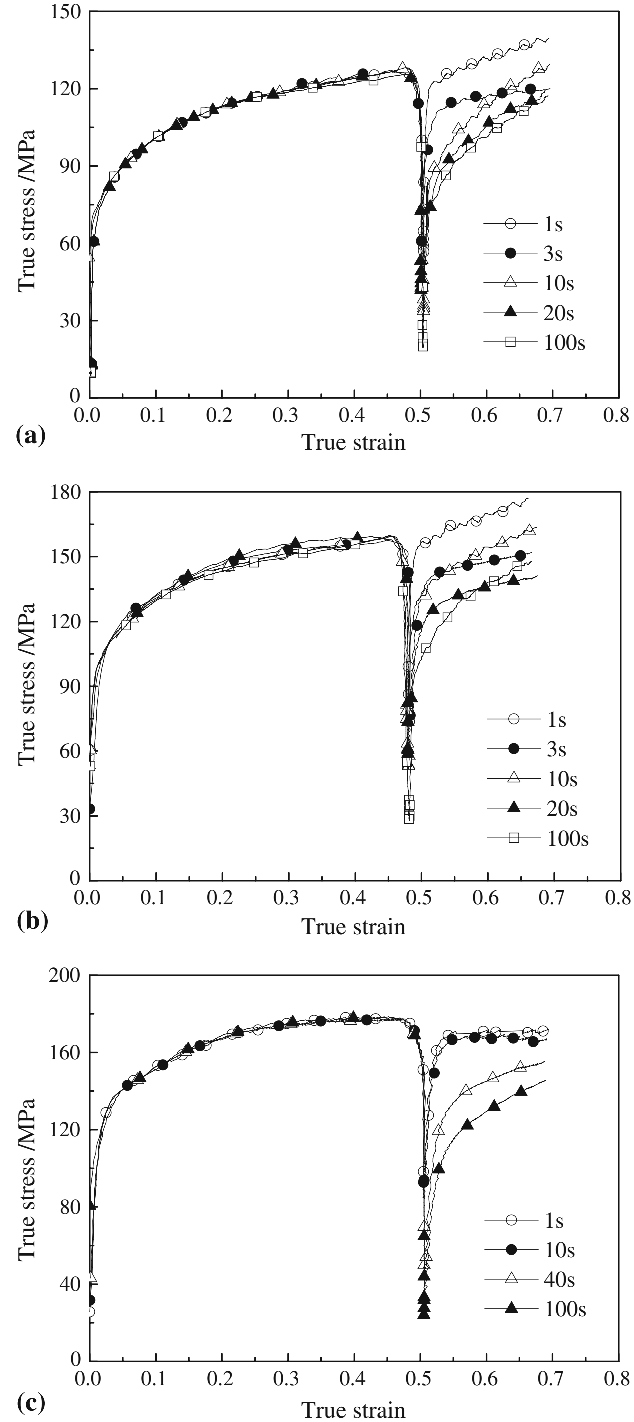

Fig. 2 True stress-strain flow curves for different interpass time at strain rate of 1 s^{-1}: (a) 800 °C, (b) 750 °C, (c) 700 °C

Fig. 2. It can be seen that the flow stress decreases with the increase in deformation temperature. When the heat treatment history and deformation schedule of the specimens are the same, the yield stress of the second deformation generally decreases with the increase of interpass time. The results indicate that static softening of the tested steel occurs during the interpass time.

The dependence of the fractional softening (X) on the interpass time for each testing temperature is shown in Fig. 3.

It has been proved that deformation temperature is the most important factor that influences the static softening behaviors. In general, the deformation temperature and recrystallization kinetics remain as an exponential function. In this test, the interpass holding temperature is the deformation one. When the other conditions are certain, the higher the deformation temperature, the faster the static softening is. When deformed at 800 °C, the fractional softening increases rapidly at a short interpass time. When the interpass time is 10 s, the fractional softening is almost 80%. When deformed at 700 °C, the fractional softening increase slowly at a short interpass time. When the interpass time is 10 s, the fractional softening is less than 20%. When the interpass time is long enough, the fractional softening can reach 100%. Figure 3, shows that $t_{0.5}$ are 3.5, 8.5, and 24 s, respectively, when deformed at 800, 750, and 700 °C.

3.2 The Kinetics of Static Softening

The kinetics of static softening are usually described by an Avrami equation (Ref 10, 11):

$$X = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^n\right] \quad \text{(Eq 2)}$$

where X is static softening, $t_{0.5}$ is the time for the softening fraction of 50%, and n is a constant. The expression most widely used for $t_{0.5}$ is (Ref 10, 11):

$$t_{0.5} = A\varepsilon^p\dot{\varepsilon}^q \exp\left(\frac{Q_{\text{rex}}}{RT}\right) \quad \text{(Eq 3)}$$

where A, p, and q are material-dependent constants, ε is the true strain, and $\dot{\varepsilon}$ is the strain rate, Q_{rex} is the apparent activation energy of recrystallization (kJ/mol), T is the absolute temperature (K), and R is the gas constant (J/mol K). Equation (3) can also be written as follows:

$$\ln t_{0.5} = \ln A + p\ln\varepsilon + q\ln\dot{\varepsilon} + \frac{Q_{\text{rex}}}{RT} \quad \text{(Eq 4)}$$

For the same condition of deformation, the static softening of the steel can be indicated by activation energy of static softening (Q_{rex}). In general, for steel, ln $t_{0.5}$ and $1/T$ maintain

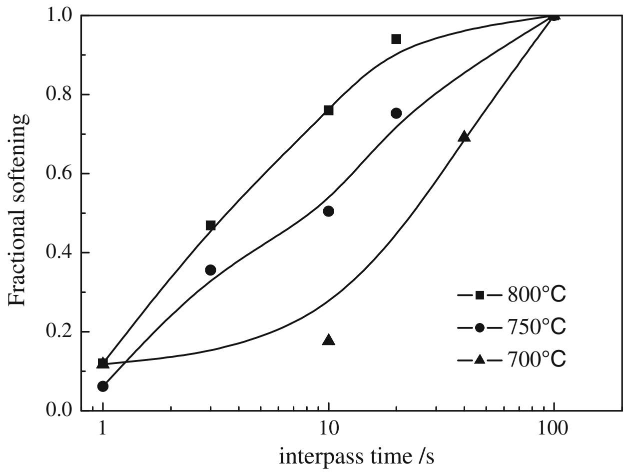

Fig. 3 Dependence of fractional softening and interpass time at strain rate of 1 s^{-1}

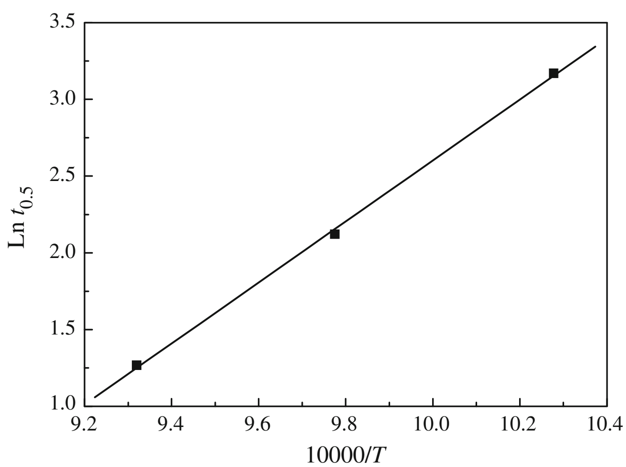

Fig. 4 Dependence of 50% fractional softening and deformation temperature

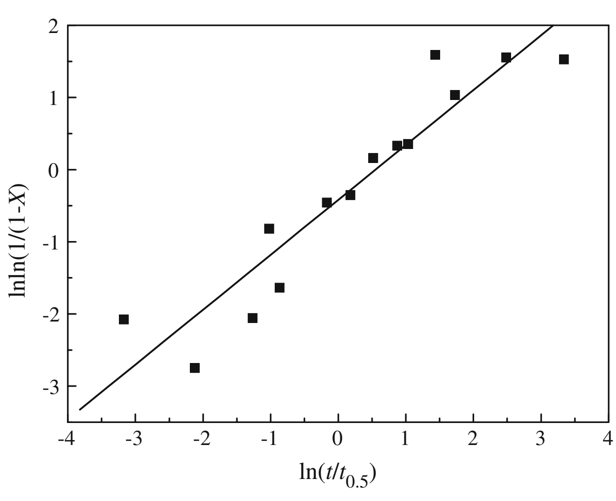

Fig. 5 Dependence of ln ln($1/(1-X)$) and ln($t/t_{0.5}$)

linear dependency, and the slope is Q_{rex}/R. On the basis of experimental data, $t_{0.5}$ at different temperatures can be obtained, and the dependence of ln $t_{0.5}$ and $1/T$ can be drawn as shown in Fig. 4. Through regression analysis, it is found that Q_{rex} is 165 kJ/mol for the tested steel deformed at the ferritic rolling temperature range, which was close to that (Q_{rex} = 173 kJ/mol) of a IF steel reported in literature (Ref 12).

In order to acquire more information about physical metallurgy of the tested steel in the process of static softening, the Avrami equation was adopted to analyze the fractional softening. Equation (2) may be rewritten as:

$$\ln\ln\frac{1}{1-X} = \ln\ln 2 + n\ln\frac{t}{t_{0.5}} \qquad \text{(Eq 5)}$$

Through linear regression analysis of the experimental data, the dependence of ln ln($1/(1-X)$) and ln($t/t_{0.5}$) is presented in Fig. 5. It can be seen that slope is 0.761, which means that n is 0.761.

Therefore, the ferritic static softening kinetics equation of the tested low carbon steel can be given as follows:

$$X = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5}}\right)^{0.761}\right].$$

4. Conclusion

The ferritic static softening behavior of a low carbon steel has been studied by double hot compression tests. It was found that the deformation temperature is the most important factor that influences the fractional softening. The higher the deformation temperature, the faster the static softening is. At the same time, the fractional softening increases gradually with the increase of the interpass time. The ferritic static softening activation energy (Q_{rex}) is 165 kJ/mol, and the ferritic static softening kinetics follows the Avrami equation.

Acknowledgment

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