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The kinetics of dynamic recrystallization of a low carbon vanadium-nitride microalloyed steel

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ABSTRACT

Single-pass compression tests were performed on a Gleeble-3800 thermo-mechanical simulator to study the dynamic recrystallization behavior of a low carbon vanadium-nitride microalloyed steel at the temperature in the range from 900 °C to 1050 °C and strain rate in the range from 0.1 s^{-1} to 10 s^{-1}. Based on the flow curves from the tests, the effects of temperature and strain rate on the dynamic recrystallization behavior were analyzed. With the assistance of the process parameters, constitutive equations were used to obtain the activation energy and hot working equation. The strain hardening rate versus stress curves were used to determine the critical stress (strain) or the peak stress (strain). The dependence of the characteristic values on Zener–Hollomon was found. The dynamic recrystallization kinetics model of the tested steel was constructed and the validity was confirmed based on the experimental results.

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1. Introduction

Material microstructure evolution and flow behavior are complex during hot forming processes, which have a close relation to the shape of flow curves. Dynamic recovery (DRV), dynamic recrystallization (DRX) and static recrystallization (SRX) processes can be identified from the flow curves. Therefore, flow curves are often used to study the flow behavior of materials, which is also an efficient approach to study DRX behavior. Since DRX process contributes to grain refinement and lower stress, which play an important role in the formability, microstructure and mechanical properties of materials [1], it is of great practical importance to study the DRX that occurs during hot forming processes. At present, there are a considerable amount of researches on the DRX behavior of vanadium microalloyed steels or vanadium and titanium microalloyed steels [2,3]. In general, the steels with higher vanadium and lower nitrogen addition were tested. However, there are few researches on the steel with lower vanadium and higher nitrogen addition. Furthermore, it has been reported that nitrogen is a cost effective microalloyed element in vanadium microalloyed steel and it plays an important role in the effect of vanadium on the microstructure or properties of steels [4,5].

In the present work, single-pass compression tests were performed on a Gleeble-3800 thermo-mechanical simulator to study the DRX behavior of a low carbon vanadium-nitride microalloyed steel. Based on the flow curves, the effects of temperature and strain rate on the DRX behavior of the tested steel were analyzed. The DRX kinetics equations of the tested steel were established by the regression method. At last, the predicted results and experimental ones were compared.

2. Material and experiments

In this work, the low carbon vanadium microalloyed steel with chemical composition of C 0.19, Mn 1.5, Si 0.37, V 0.06, Ti 0.019, S 0.0095, P 0.0087, N 0.0160 and balance iron (wt%) was used.

The tested steel was from the continuous casting slab as received. The specimens with height of 12 mm and diameter of 8 mm were prepared. In order to reduce the occurrence of inhomogeneous compression, special anvils were employed. Both ends of the specimen were covered with tantalum foils to prevent adhesion between specimen and anvils. The specimens were austenitized at 1150 °C for 5 min and cooled with the rate of 5 °C/s to deformation temperature and held there for 1 min before compression. Single-pass compression tests were carried out at the temperature in the range from 900 to 1050 °C with an interval of 50 °C and strain rates of 0.1, 1, 3 and 10 s^{-1}.

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3. Results and discussion

3.1. Flow curves analysis

Fig. 1 presents the flow curves under different deformation conditions. At the early stage of deformation, the stress increases proportionally to the strain, which leads to the increase in dislocation density and distortion in the steel. The strain hardening process is identified. At the second stage, the strain hardening effect can be reduced due to dislocation slipping, rearranging or eliminating. And the strain hardening rate keeps falling with the increase in strain. When the strain hardening rate is equal to zero, the stress reaches the peak. In Fig. 1, the flow curves exhibit typical peaks at the lower strain rate of 0.1 s^{-1}. At the same strain rate and strain, the stress or the peak stress increases with the decrease in temperature. Since dislocation movement is restrained at lower temperature, it contributes to a higher strain hardening rate and results in a higher stress. At higher strain rate, strain hardening and dynamic recovery play the main role and no typical peak is recognizable. In Fig. 1b, it can be seen that the flow curve corresponding to strain hardening and dynamic recovery process is typical at a strain rate higher than 3 s^{-1}.

3.2. Determination of critical conditions

Poliak and Jonas [6,7] have proposed the critical condition kinetics based on the thermal irreversible principles and the critical conditions for the initiation of DRX can be determined by analyzing the relation between strain hardening rate and flow stress. It is a easier approach and widely used [7,8]. At the beginning of deformation, the softening induced by DRV is fast and strain hardening rate decreases with the increase of stress, which corresponds to the beginning of the sub-grain formation. At the second stage of deformation, the increase rate of softening rate decreases during the sub-grain forming process. When the stress reaches a critical value, the increase rate of softening rate suddenly increases due to onset of DRX, which leads to an inflection in the plot of strain hardening rate versus stress. The stress at the inflection point is identified as the critical stress. When a balance between strain hardening and softening reaches, the strain hardening rate would reduce to zero and the corresponding stress is identified as the peak stress.

The flow curves under different deformation conditions were processed and analyzed by this method to determine the critical conditions of the tested steel. The experimental curves are not mathematically smooth and there are some irregularities and fluctuations, which can make it impossible for the following differentiations. To eliminate the irregularities and fluctuations in the experimental curves, the flow curves were fitted by the ninth-order polynomial and good fitting curves were obtained. The resultant strain hardening rate θ versus stress curves are shown in Fig. 2. The inflection points and the zero points in the curves are marked out. Therefore, the critical stress σ_c (strain ε_c) or the peak stress σ_p (strain ε_p) can be obtained. Fig. 3 presents the relationship between σ_c (ε_c) and σ_p (ε_p). A linear relationship is recognizable and R is the linear correlation coefficient. By linear regression, the following formulas can be obtained:

$$\sigma_c = 0.90285\sigma_p \quad (1)$$

$$\varepsilon_c = 0.48046\varepsilon_p \quad (2)$$

In Sellars' research [9], the ratio of critical strain to peak strain generally falls in the range of 0.6–0.85. However, lower values for some microalloyed steel have been reported and they are in the range of 0.4–0.55 [10,11]. Since 0.4804 falls in the range, it is reasonable. Compared with the previous work on vanadium microalloyed steel [12], the value is higher, which maybe related to the higher nitrogen addition.

3.3. Activation energy and hot working equation

The flow stress of material is related to process parameters and chemical compositions during hot working processes. With

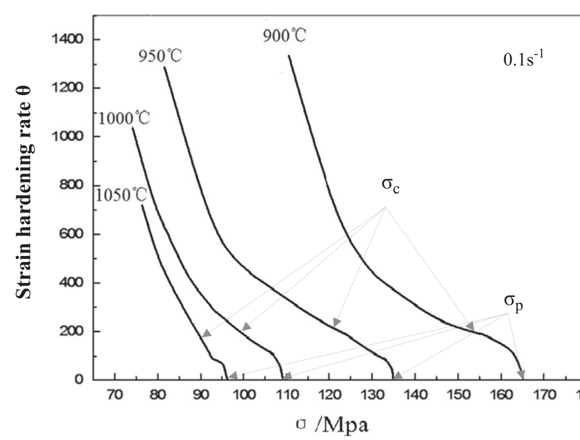

Fig. 2. Strain hardening curves of the tested steel at different temperatures.

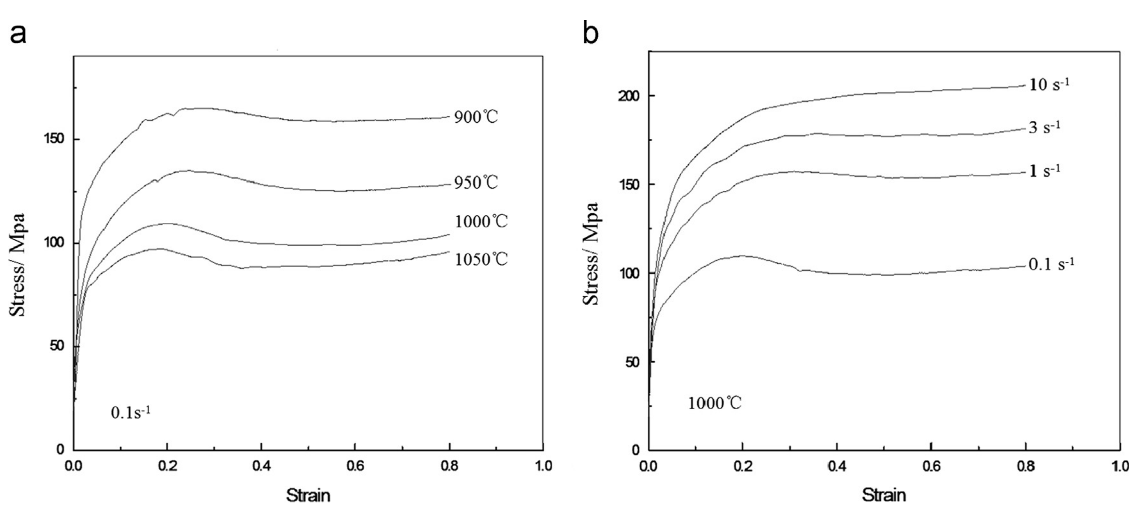

Fig. 1. Flow curves obtained for different deformation conditions.

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