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Quantitative Analysis of Work Hardening and Dynamic Softening Behavior of low carbon alloy Steel Based on the Flow Stress

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ABSTRACT

In this study, the constitutive equation and DRX(Dynamic recrystallization) model of Nuclear Pressure Vessel Material 20MnNiMo steel were established to study the work hardening and dynamic softening behavior based on the flow behavior, which was investigated by hot compression experiment at temperature of 950 °C, 1050 °C, 1150 °C and 1250 °C with strain rate of 0.01 s^{-1}, 0.1 s^{-1} and 10 s^{-1} on a thermo-mechanical simulator THE RMECMASTOR-*Z*. The critical conditions for the occurence of dynamic recrystallization were determined based on the strain hardening rate curves of 20MnNiMo steel. Then the model of volume fraction of DRX was established to analyze the DRX behavior based on flow curves. At last, the strain rate sensitivity and activation volume V^* of 20MnNiMo steel were calculated to discuss the mechanisms of work hardening and dynamic softening during the hot forming process. The results show that the volume fraction of DRX is lower with the higher value of *Z* (Zener–Hollomon parameter), which indicated that the DRX fraction curves can accurately predicte the DRX behavior of 20MnNiMo steel. The storage and annihilation of dislocation at off-equilibrium saturation situation is the main reason that the strain has significant effects on SRS(Strain rate sensitivity) at the low strain rate of 0.01 s^{-1} and 0.1 s^{-1}. While, the effects of temperature on the SRS are caused by the uniformity of microstructure distribution. And the cross-slip caused by dislocation piled up which beyond the grain boundaries or obstacles is related to the low activation volume under the high *Z* deformation conditions. Otherwise, the coarsening of DRX grains is the main reason for the high activation volume at low *Z* under the same strain conditions.

1. Introduction

20MnNiMo is low carbon low alloy steel with moderate strength, superior plasticity and toughness, good ductility and weldability. While, 20MnNiMo steel is usually used in manufacture of large and medium-sized nuclear reactor pressure vessel due to its low neutron irradiation sensitivity and superior performance. It is necessary to study its flow behavior and hot deformation mechanisms. For the existing literature, Sheng et al. studied grain refinement of 20MnNiMo steel during heat treatment process [1], Zhang Meng, et al. described the composition microstructure, HT processing and mechanical properties of 20MnNiMo rolling steel plate with the thickness of 390 mm [2], Therefore, There is only a few literature about the 20MnNiMo steel, Which mainly about welding performance, heat treatment and the effect of alloy elements on its properties [3,4], While there is no study about flow behavior and hot deformation mechanisms of 20MnNiMo steel. So this study will have a deep discussion on the work hardening and dynamic softening behavior of 20MnNiMo steel based on the flow stress.

Dynamic softening and work hardening can frequently occur during the hot deformation of metal, which can lead to annihilation and rearrangement of dislocations. The DRV (dynamic recovery) proceeds sluggishly at the initial stage of deformation and leads to the accumulation of dislocation until the dislocation density reaches a critical value for triggering DRX [5,6]. Many studies have been conducted to study the typical flow curve of DRX [6–8]. The general model for DRX is that the nucleation of DRX grains starts at a critical strain, which is a function of initial microstructure and deformation conditions. Then the evolution of DRX microstructure proceeds with the formation of a necklace structure by further deformation [9]. Moreover, Cingara and Mcqueen [10] had conducted some researches to study the work hardening region of the DRX by using the empirical equations, which can well describe the DRX behavior. Nevertheless, it should be noted that the kinetics model of DRX volume fraction determined by the nucleation rate and grain boundary mobility, which are directly influenced by work hardening behavior [8] and grain boundary mobility of recrystallizing grains is proportional to the difference of dislocation density between the outside and inside recrystallizing grains [11]. The work

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hardening can affect the deformability, ductility and toughness of materials intimately [12] as well as the softening behaviors [6]. The common method used to analysis the softening and work hardening behavior during hot deformation is the metallographic observations, although few attentions have paid to investigate the softening and work hardening behavior through quantitative analysis of true stress–strain curves collected by hot compression tests.

In present work, the critical conditions for DRX of 20MnNiMo steel during hot compression was determined using the work hardening rate versus true stress under different hot deformation conditions, then the kinetics of DRX was analyzed by constructing the model of volume fraction of DRX based on flow curves. At last, the work hardening and softening behavior of 20MnNiMo steel was discussed in detail by calculating the value of SRS and activation volume V^* at various deformation conditions, which combined with flow behavior and DRX mechanism.

2. Experimental details

The material used in this investigation and compression test at temperature [13] was 20MnNiMo low carbon alloy steel and its chemical compositions of the material are given in Table 1. According to the components, a casting ingot with 30 mm in diameter and 200 mm in height was manufactured and the processing of homogenizing annealing heat treatment was conducted in a high temperature and high vacuum annealing furnace. Cylindrical compression specimens with 8 mm in diameter and 12 mm in height were machined parallel to vertical axis from the as-cast steel by electric spark line cutting. Then, the hot simulation compression tests of 20MnNiMo steel were conducted at strain rate of 10 s^{-1}, 1 s^{-1}, 0.1 s^{-1}, 0.01 s^{-1} and forming temperature of 950 °C, 1050 °C, 1150 °C, 1250 °C on a hot simulation test machine called THE RMECMASTOR-*Z* with a 60% of height reduction rate. Otherwise, the specimens were heated to deformation temperatures with a heating rate of 20 °C s^{-1} and held 3 min to ensure a uniform temperature by resistance heating thermocouple-feedback-controlled AC current before compression and then the compressed sample was water quenched immediately.

3. Constitutive modeling

3.1. Flow stress behavior

The true stress–true strain curves of 20MnNiMo steel at different strain rate and temperature are shown in Fig. 1, according to the characteristics of flow stress curves, we can got that the flow stress increases with the increasing of strain rate and stress decreases with the increasing of deformation temperature. The reason for the change is that higher strain rate or lower temperature provide shorter time for energy accumulation and lower grain boundaries mobilities which result in the phenomenon that the effect of work hardening is stronger than the effect of dynamic softening. However, the softening behavior is more significant since the rate for cross-slip of screw dislocation and climb of edge dislocations increase with decreasing of flow stress at a higher temperature [14], which is consistent with the variation of the flow stress curves shown in Fig. 1 that the softening behavior at temperature of 1250 °C is more obvious than it is at other lower temperature (950 °C, 1050 °C, 1150 °C). Otherwise, reduction of deformation is an important factor for the flow behavior of 20MnNiMo steel, most curves (0.01 s^{-1} and 1.0 s^{-1} at 950 °C, 1050 °C, 1150 °C, and 11250 °C) in Fig. 1 exhibit a significant single peak stress followed by a gradual fall to a steady state stress which indicates that the typical DRX behavior occurs with the increase of strain [15,16]. In the initial deformation stage, the stress increases abruptly because of the influence of work hardening, then the increasing rate of curves decrease with the increase of strain due to the occurrence of dynamic recrystallization or dynamic recovery untill reaching the flow stress peak, when the softening rate is higher than hardening rate due to the enough energy of dynamic recrystallization provided by high strain, the stress reduce gradually until a new balance between softening and hardening is achieved.

Table 1
The main chemical composition of 20MnNiMo steel (%, mass fraction).

C	Si	Mn	Ni	Mo	Cr	S	P	V	Cu	Al
0.20	0.16	1.39	0.80	0.50	0.15	0.003	0.005	0.005	0.04	0.02

3.2. Constitutive equations for flow behavior

In hot deformation of metallic materials, the deformation behavior is commonly expressed by the empirical function including activation energy at different temperature and strain rates [17,18].

$$\dot{\varepsilon} = AF(\sigma)\exp\left(-\frac{Q}{RT}\right) \tag{1}$$

Where $F(\sigma)$ is a function of flow stress with the following equations,

$$\begin{aligned} F(\sigma) &= \sigma^{n} && \text{if } \alpha\ \sigma < 0.8 \\ &= \exp(\beta\sigma) && \text{If } \alpha\ \sigma < 1.2 \\ &= [\sinh(\alpha\sigma)]^{n'} && \text{For all value of } \sigma \end{aligned} \tag{2}$$

Where $\dot{\varepsilon}$ is strain rate, R is the gas constant (8.31 J mol^{-1} K^{-1}), T is the absolute temperature, Q is the activation energy of deformation, σ is the flow stress and α, β, n, n, A are the constants ($\alpha = \beta/n$). The effects of temperature and strain rate on deformation behavior can be represented by a temperature compensated strain rate factor, the Zener–Hollomon parameter Z:

$$Z = \dot{\varepsilon}\exp\left(-\frac{Q}{RT}\right) \tag{3}$$

In order to determine the constant parameters, the peak stress of flow stress was used as the input parameters for the linear regression process. By substitution of $F(\sigma)$ from Eq. (2) to Eq. (1) and taking the natural logarithm from each side of the resulting equations, the following expressions could be derived for peak stress:

$$\ln(\dot{\varepsilon}) + \frac{Q}{RT} = \ln(B) + n\ln(\sigma_p) \tag{4}$$

$$\ln(\dot{\varepsilon}) + \frac{Q}{RT} = \ln(C) + \beta\ln(\sigma_p) \tag{5}$$

$$\ln(\dot{\varepsilon}) + \frac{Q}{RT} = \ln(A) + n'\ln[\sinh(\alpha\sigma_p)] \tag{6}$$

It is easy to obtain the values of n and β at constant deformation temperature from the slope of the plots shown in Fig. 2(a) and (b) ($\ln(\dot{\varepsilon})$ versus $\ln(\sigma_p)$ and $\ln(\dot{\varepsilon})$ versus σ_p) based on Eqs. (4) and (5) and the values of constant parameters are shown as follows [19,20–25]: $\alpha = 6.896882$, $\beta = 0.09175$, $n = 6.896882$.

The hot deformation active energy Q can be severed as a significant indicator of the deformation difficulty degree and it can derived from the Arrhenius plots of ln [sinh ($\alpha\sigma p$)] versus $1/T$ shown in Fig. 2(c) [20,21,25–28], the Q value of 20MnNiMo steel is 540.4332 kJ/mol. Hot deformation equation of 20MnNiMo steel is shown as Eq. (7) and the flow stress are expressed as Eq. (8).