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Physically based constitutive analysis to predict flow stress of medium carbon and vanadium microalloyed steels

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ABSTRACT

Two medium carbon steel grades were used in the present investigation. One of them was microalloyed with vanadium. Both steel grades were subjected to hot compression tests on the Gleeble-1500 thermo-mechanical simulator in the temperature range of 900–1100 °C and strain rate range of 0.01–10 s^{-1}. Constitutive relationships of both steels were investigated by the physically based approach incorporating the strain effect, which accounts for the dependence of Young's modulus and the self-diffusion coefficient of austenite on temperature. The accuracy and reliability of the equations was quantified by employing statistical parameters such as the correlation coefficient and absolute average error. The results showed that the proposed equations can predict the flow stress of the experimental steels with acceptable accuracy, thus may be an alternative method for predicting the flow stress in hot working.

1. Introduction

Medium carbon steels and medium carbon vanadium microalloyed steels are being widely used for machinery structural parts [1]. In particular, medium carbon vanadium microalloyed steels do not require heat treatment after they are shaped into parts, as the mechanical properties are obtained directly at the end of the process, so an important saving of costs and energy can be reached [2,3]. In order to improve the properties of this material, the parameters of the forming process must be controlled carefully. During hot working of plain carbon steels, the microstructure development is not as pronounced, as can be observed in the case of microalloyed steels that contain small amounts of Ti, Nb, Al or V singly or in combination [4].

The modeling of hot flow stress during hot working using constitutive equations is quite important in metal-forming processes. There are quite a lot of works focused on the conventional hyperbolic sine constitutive equation for determining apparent materials constants [5–15]. However, it is considered that the classical description of the flow behavior under hot working conditions generally takes no account of the internal microstructure, leading to apparent rather than actual values in the constants considered [16–18]. So a few works have introduced a new physically based method (Eq. (5)) with constant creep exponent 5, which accounts for the dependence of Young's modulus and the self-diffusion coefficient of austenite on temperature [16–20].

$$\dot{\varepsilon}/D(T) = B[\sinh(\alpha'\sigma/E(T))]^5 \quad (1)$$

where $D(T) = D_0 \exp(Q_{sd}/RT)$ with Q_{sd} being the self-diffusion activation energy, $E(T)$ describes the dependence of Young's modulus on temperature. The values of D_0, Q_{sd} and $E(T)$ can be determined from the tables given by Frost and Ashby [21,22].

Nowadays, there is no report on the physically based constitutive equation incorporating the strain effect to predict hot deformation flow stress of steels. So the aim of this paper is to study the constitutive relationships of a C–Mn steel and vanadium microalloyed steel using this method. The results of this paper can be reference for further research and application of the physically based constitutive equation.

2. Experimental materials and procedures

The chemical composition of the materials used in this investigation is given in Table 1.

The experimental steel was melted and casted into an ingot of 50 kg in vacuum induction furnace, hot forged into rods. Samples of ⌀8 × 15 mm^2 were cut-off from the rods. The compression tests were carried out on a Gleeble-1500 thermo-mechanical simulator in the temperature range from 900 °C to 1100 °C at an interval of 50 °C and at constant true strain rates of 0.01, 0.1, 1 and 10 s^{-1}. A thermocouple was spot welded to the longitudinal center of the

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Table 1
Chemical composition of the experimental steels (wt%).

C	Mn	Si	V	S	P	Al	N
0.36	1.42	0.27	–	0.0045	0.0053	≤0.005	0.0045
0.37	1.46	0.38	0.089	0.0042	0.0058	≤0.005	0.0071

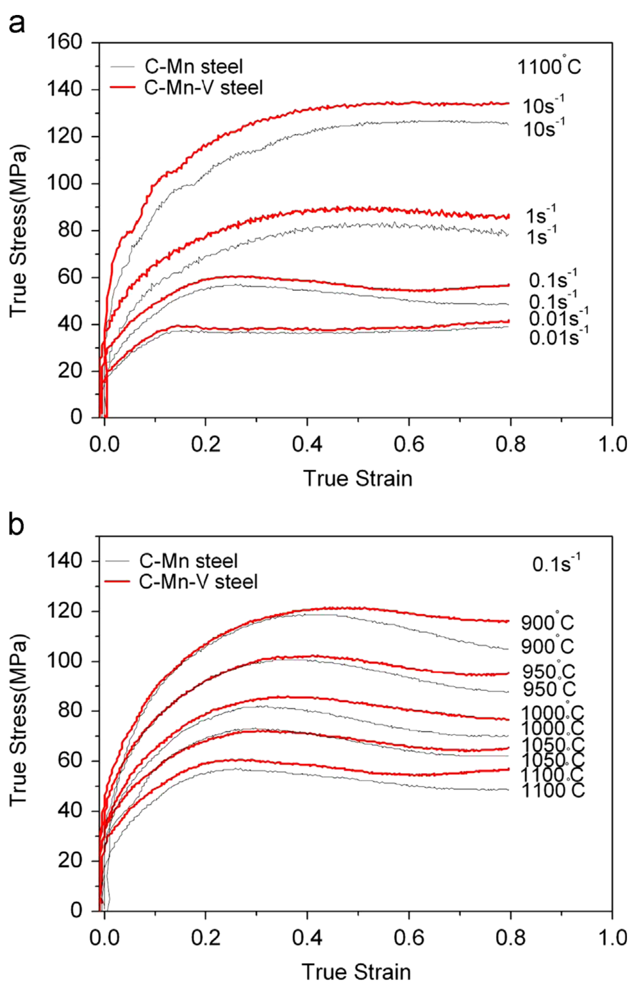

Fig. 1. Flow curves obtained at different deformation conditions: (a) 1100 °C and (b) 0.1 s^{-1}.

specimen to monitor the temperature. The stimulator was equipped with a control system to induce the exponential decay of the actuator speed to obtain a constant strain rate. Prior to the compression, specimens were heated in vacuum at the rate of 10 K s^{-1} to 1150 °C, the soaking time was 5 min for C–Mn–V steel and 3 min for C–Mn steel, then they were cooled to the deformation temperature with the cooling rate of 6.7 K s^{-1}. All specimens were kept at the test temperature for 30 s before compression. Specimens were deformed to a strain of 1.0, then they were water quenched immediately to room temperature. The true stress–true strain curves were constructed using the load-stroke data obtained from the compression tests.

3. Results and discussion

3.1. True stress and true strain

Fig. 1 shows the stress–strain curves of the steels deformed at different temperatures and strain rates. It can be found that the flow stress of the experimental steels increases with the decrease of temperature and the increase of strain rate. At the temperature of 1100 °C, the steels exhibit a typical dynamic recrystallization (DRX) behavior at 0.01 s^{-1} and 0.1 s^{-1}, the stress rising to a peak followed by softening towards a steady state region, while at higher strain rates (1 s^{-1} and 10 s^{-1}), the amount of flow softening is smaller. At the strain rate of 0.1 s^{-1}, the steels exhibit a typical DRX behavior at all temperatures, indicating the occurrence of DRX. From Fig. 1, it is seen that the peak strain and the peak stress of the experimental steels increase with the decrease of temperature and the increase of strain rate. It can also be found from Fig. 1 that the C–Mn–V steel has a higher flow resistance than the C–Mn steel at the same deformation conditions, indicating that V offers effects as a solid solution strengthener, which is in reasonable agreement with some reports before [23,24].

3.2. Physically based constitutive equation with creep exponent 5

In the Frost and Ashby tables [21,22], γ-iron is the material most similar to the experimental steels used here. Therefore, the Frost and Ashby data for γ-iron was used in the present study and the following expressions were obtained for $D(T)$ and $E(T)$ of the experimental steels.

$$D(T)=D_0\exp\left(\frac{-Q}{RT}\right)=1.8\times10^{-5}\exp\left(\frac{-270,000}{RT}\right) \quad (2)$$

$$E(T)=E_0\left(1-\frac{T_M}{G_0}\frac{dG}{dT}\frac{(T-300)}{T_M}\right)=2.16\times10^5\left(1-0.91\frac{(T-300)}{1810}\right) \quad (3)$$

There are two unknown parameters, B and α', to be determined in Eq. (1). In order to find the value of α', a new approach was introduced by Mirzadeh et al. [19], which only required a linear regression and was easy to apply. In this approach, Eqs. (4) and (5) were introduced as follows:

$$\dot{\varepsilon}/D(T)=B_1(\sigma/E(T))^{n'_1} \quad (4)$$

$$\dot{\varepsilon}/D(T)=B_2\exp(\beta'\sigma/E(T)) \quad (5)$$

The value of α' can be calculated from $\alpha'=\beta'/n'_1$, with the value of n'_1 and β'obtained from the slope of the lines $\ln(\dot{\varepsilon}/D(T))$– $\ln(\sigma/E(T))$ and $\ln(\dot{\varepsilon}/D(T))-\sigma/E(T)$ plots, respectively. Fig. 2 shows both the experimental data and regression results of $\ln(\dot{\varepsilon}/D(T))-\ln(\sigma_p/E(T))$ (Fig. 2(a)) and $\ln(\dot{\varepsilon}/D(T))-\sigma_p/E(T)$ (Fig. 2(b)) plots for both the experimental steels. The linear regression of these data results in the value of $\alpha'=1122.21806$ for C–Mn steel and $\alpha'=1265.248379$ for C–Mn–V steel.

According to Eq. (1), the slope of the plot of $(\dot{\varepsilon}/D(T))^{1/5}-\sinh(\alpha'\sigma_p/E(T))$ by fitting a straight line with an intercept of zero ($y=ax+0$) was used to obtain the value of $B^{1/5}$=950.02433 for C–Mn steel and $B^{1/5}$=783.2518 for C–Mn–V steel (Fig. 3). Therefore, the resultant constitutive equations can be expressed as

C–Mn steel:

$$\dot{\varepsilon}\exp(270,000/RT)=1.39298\times10^{10}[\sinh(1122.21806\times\sigma_p/E(T))]^5 \quad (6)$$

C–Mn–V steel:

$$\dot{\varepsilon}\exp(270,000/RT)=5.30615\times10^{9}[\sinh(1265.248379\times\sigma_p/E(T))]^5 \quad (7)$$

Actually, the calculations above only take into account the stress corresponding to peak strain but with no consideration of all strains. So a series of constitutive equations (Eq. (1)) with different material constants α' and $\ln B$ for different strain values