High temperature deformation behavior and constitutive modelling for 05Cr17Ni4Cu4Nb stainless steel

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Abstract

The high temperature deformation behavior of 05Cr17Ni4Cu4Nb stainless steel was investigated at the temperatures from 1000 to 1200°C and strain rates from 0.01 to 10s−1 on Gleeble-3500 thermo-simulation machine. The stress-strain curves at lower strain rate (0.01-0.5 s−1) exhibit a single peak stress, indicating a typical dynamic recrystallization (DRX) behavior of the steel, but at higher strain rates (10 s−1), the temperature rise due to the heat liberated from severe plastic deformation leads to the final drop of flow stress. Further microstructural observation confirmed the occurrence of DRX behavior, the average grain sizes decreased with the increasing strain rate and the decreasing deformation temperature, and the higher the deformation temperature, the larger the DRX degree. A new constitutive equation incorporating the effect of the strain on the deformation behavior was proposed based on the Arrhenius-type equation, in which the material constants \( I \), \( n \), \( Q \) and \( A \) were found to be polynomial functions of strain. The stress-strain relations of 05Cr17Ni4Cu4Nb steel predicted by the proposed constitutive equation agreed well with experimental results.

Keywords: 05Cr17Ni4Cu4Nb steel; Deformation behavior; Microstructure evolution; Constitutive equation

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1. Introduction

Material flow behavior is often complex during the hot deformation process. The hardening and softening mechanisms are both significantly affected by the deformation temperature and strain rate (Mandal et al., 2009). The understanding of the basic behavior of metals and alloys under hot deformation conditions is of vital importance for the design of metal forming processes such as hot rolling, forging and extrusion (Rao et al., 2011). The constitutive equation, which is the mathematical representation of the deformation behavior of a material, has been used to develop the reasonable processing technology or as input to the Finite Element code for simulating the response of the material under specified loading conditions (Li et al., 2013). Therefore, a lot of researchers began to concentrate their attention on developing the constitutive equation of flow stress by use of the advanced modelling technique. The hyperbolic sine Arrhenius-type constitutive model has been successfully applied to predict the high temperature deformation behavior of materials. This model was proposed by Sellars et al. (1966) where the flow stress is expressed by the sine-hyperbolic laws in an Arrhenius-type equation and the original model has been revised several times to suitably represent the high temperature deformation behavior of various alloys. Sloof et al. (2007) introduced a strain-dependent parameter into the Arrhenius-type constitutive equation in order to make their model predict the deformation behavior of a wrought magnesium alloy more accurately. Lin et al. (2008) revised the models to describe the flow behaviors of 42CrMo steel by compensation of strain and strain rate, and afterwards many researchers used this modified model to predict the high temperature flow behaviors of various materials. Cai et al. (2011) carried out constitutive analysis of Ti-6Al-4V alloy using this revised Arrhenius-type model and the good agreement between the experimental data and the predicted results indicates that the modified model is valid. Li et al. (2012) established the strain-compensated constitutive equations and used them to predict the flow behaviors of 7050 aluminium alloy successfully. In addition, Xiao et al. (2011) proposed a new modification method to revise the Arrhenius equation, and their model could accurately predict the high temperature flow stress of 1Cr12Ni3Mo2VNbN martensitic steel. Feng et al. (2014) employed the exponential law and the hyperbolic sine-type constitutive equation to describe the relationship among flow stress, deformation temperature and strain rate for 20CrMnTiH steel at the strain rate range of 0.01-0.1s^{-1} and 1-5s^{-1}, respectively, the peak stress values predicted by the proposed constitutive model agreed well the corresponding experimental results.

05Cr17Ni4Cu4Nb, a martensitic hardening stainless steel developed indigenously in China, has been used to make steam turbine blades in light water reactors and pressurized water reactors, due to its excellent combination of mechanical properties and corrosion resistance. The steam turbine blades for this steel are mainly manufactured by hot forging, so it is very important to understand the high temperature deformation behavior of this steel. The present paper aims to evaluate the flow behavior of 05Cr17Ni4Cu4Nb steel by hot compression tests and to analyse the deformation mechanisms by microstructural observation under various deformation conditions. Based on the experimental data, a constitutive equation incorporating the effects of the strain, strain rate and deformation temperature is derived to describe the plastic flow property.

2. Experimental procedure

The experimental material is 05Cr17Ni4Cu4Nb steel with the chemical composition of 15.2-16.4%Cr, 3.8-4.5%Ni, 3.0-3.7%Cu, 0.15-0.35%Nb, C≤0.55%, Si≤1.0%, Mn≤0.5%. The hot compression tests were performed on Gleeble-3500 thermo-simulation machine in five different temperatures (1000, 1050, 1100, 1150 and 1200°C) and five different strain rates (0.01, 0.1, 0.5, 2.5 and 10 s^{-1}). Each specimen was heated to the deformation temperature at a rate of 10°C/s by thermo-coupled feedback-controlled AC current, and held for 5 min at isothermal conditions before compression test to obtain the heat balance. The reduction in height was 60% at the end of the compression tests. The true stress-true strain curves were constructed by using the load-stroke data obtained from the compression tests.

After deformation, the specimens were water-quenched, to avoid microstructure modification during slow cooling from the testing temperature. The deformed specimens were sectioned along the longitudinal compression axis. Then, the sections were polished and etched in the etching solution of 5gFeCl₃ + 10mLHCL + 100mLH₂O. The microstructure in the center region of the section plane was examined by the optical microscope.
3. Results and discussion

3.1. True stress-strain curve

The true stress-strain curves of 05Cr17Ni4Cu4Nb steel obtained at different temperatures and strain rates are shown in Fig. 1. Most of the curves exhibit typical DRX behavior with a single peak stress followed by a gradual fall toward a steady-state stress. However, the peak stress becomes less obvious when the strain rate is increased or the deformation temperature is decreased. The stress-strain curves also show that the flow stress decreases as the deformation temperature increases or the strain rate decreases. The drop in flow stress with deformation temperature may be attributed to the increase in the rate of restoration processes and the decreases in the strain-hardening rate. Additionally, the temperature rise due to the heat liberated from the plastic deformation at higher strain rates (10 s⁻¹) leads to the final drop of flow stress.

Fig. 1. True stress-strain curves of 05Cr17Ni4Cu4Nb steel under different deformation temperatures and strain rates: (a) 1000°C; (b) 1050°C; (c) 1100°C; (d) 1150°C and (e) 1200°C.

3.2. Microstructure evolution

The microstructure of 05Cr17Ni4Cu4Nb steel during the hot deformation is strongly influenced by the deformation temperature and strain rate. Fig. 2(a) and (b) depict the microstructures deformed at the strain rate of 2.5 s⁻¹ under the temperatures of 1050°C and 1150°C. It can be seen that higher temperature is in favor of DRX behavior, but the grain size increases with increasing deformation temperature. Fig. 2(c), (a) and (d) show the microstructures deformed at the temperature of 1050°C under the strain rates of 0.5, 2.5 and 10 s⁻¹, respectively. With increasing strain rate, the plastic deformation characteristics become increasingly obvious and the grain size decreases gradually. Additionally, the temperature rise due to the heat liberated from deformation at higher strain rates (10 s⁻¹) leads to the inhomogeneity of the microstructure (Fig. 2(d)). Therefore, it is of great significance to carefully control the deformation temperature and strain rate in the practical process.
Fig. 2. Microstructure of 05Cr17Ni4Cu4Nb steel under different temperatures and strain rates: (a) $\dot{\varepsilon} = 2.5s^{-1}$, $T = 1050^\circ$C, (b) $\dot{\varepsilon} = 2.5s^{-1}$, $T = 1150^\circ$C, (c) $\dot{\varepsilon} = 0.5s^{-1}$, $T = 1050^\circ$C and (d) $\dot{\varepsilon} = 10s^{-1}$, $T = 1050^\circ$C.

3.3. Constitutive equation for 05Cr17Ni4Cu4Nb steel

The correlation between the flow stress ($\dot{\sigma}$), temperature ($T$) and strain rate ($\dot{\varepsilon}$), particularly at high temperature, could be expressed by an Arrhenius type equation. Further, the effects of temperature and strain rate on deformation behavior could be represented by Zener-Holloman parameter ($Z$) in an exponent type equation. The two equations are mathematically expressed as,

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right),$$  \hspace{1cm} (1)

$$\dot{\varepsilon} = A F(\dot{\sigma}) \exp\left(-\frac{Q}{RT}\right),$$  \hspace{1cm} (2)

Where, $F(\dot{\sigma}) = \begin{cases} \sigma^n & \alpha \dot{\sigma} < 0.8 \\ \exp(\beta \dot{\sigma}) & \alpha \dot{\sigma} > 1.2 \\ [\sinh(\alpha \dot{\sigma})]^n & \text{for all } \dot{\sigma} \end{cases}$.

Therein, $R$ is the universal gas constant (8.31J mol$^{-1}$K$^{-1}$); $T$ is the absolute temperature (K); $Q$ is the activation energy (kJ mol$^{-1}$); $A$, $\alpha$ and $n$ are the material constants, $\alpha = \beta/n$.

Since the flow stress changes with the increasing strain (see Fig.1), the effects of strain on the material constants of constitutive equation should be considered. Taking the true strain of 0.4 as an example, the solution procedures of material constants are illustrated in Fig.3. The value of $n$ and $\beta$ can be obtained from the slope of the lines in ln$\sigma$-ln $\dot{\varepsilon}$ plot (Fig.3 (a)) and $\sigma$-ln $\dot{\varepsilon}$ plot (Fig.3 (b)), respectively. This gives the value of $\alpha = \beta/n = 0.0096$ MPa$^{-1}$. The value of $Q$, derived from the average of the slopes in the ln[$\sinh(a\dot{\sigma})$]-1/T plot (Fig. 3(c)), is 424.7962 kJ .mol$^{-1}$. The value of $A$ at a particular strain rate can be obtained by plotting the relationship between ln[$\sinh(a\dot{\sigma})$] and ln $\dot{\varepsilon}$. As shown in Fig. 3(d), the value of $A$ is 2.6134×10$^{15}$. 


Fig. 3. Evaluating the value of (a) $n$ by plotting $\ln \varepsilon$ vs $\ln \sigma$, (b) $\beta$ by plotting $\ln \varepsilon$ vs $\sigma$, (c) $Q$ by plotting $1/T$ vs $\ln \sinh(\alpha \sigma)$ and (d) $A$ by plotting $\ln \varepsilon$ vs $\ln \sinh(\alpha \sigma)$.

The values of the material constants ($\alpha$, $n$, $Q$ and $A$) of the constitutive equation are computed under the deformation strains ranging from 0.05 to 0.90 at the interval of 0.05. The relationships between the material constants ($\alpha$, $n$, $Q$, $A$) and the true strain, obtained by using polynomial fitting, are shown in Fig. 4. The polynomial fitting result of $\alpha$, $n$, $Q$ and $A$ for 05Cr17Ni4Cu4Nb steel is showed in Eq. (3),

$$
\begin{align*}
\alpha &= 0.0127 - 0.0343\varepsilon + 0.1396\varepsilon^2 - 0.1799\varepsilon^3 + 0.0625\varepsilon^4 \\
n &= 6.9511 - 14.3009\varepsilon + 2.8577\varepsilon^2 + 11.0232\varepsilon^3 - 4.9926\varepsilon^4 \\
Q &= 427.4870 - 167.1146\varepsilon + 1028.2212\varepsilon^2 - 932.8486\varepsilon^3 + 1941.5358\varepsilon^4 \\
\ln A &= 35.3126 - 17.0173\varepsilon + 79.2206\varepsilon^2 - 101.2652\varepsilon^3 + 42.6929\varepsilon^4
\end{align*}
$$

(3)

Fig. 4. Variations of (a) $\alpha$, (b) $n$, (c) $Q$ and (d) $\ln A$ with $\varepsilon$.

Fig. 5 shows part of the comparisons between the experimental and predicted results by the developed constitutive equation of 05Cr17Ni4Cu4Nb steel. It can be seen that an agreement between the experimental and calculated values is satisfactory.
Fig. 5. Comparisons between predicted and experimental flow stresses at strain rate of (a) 0.01 s⁻¹, (b) 0.1 s⁻¹, (c) 0.5 s⁻¹ and (d) 2.5 s⁻¹.

4. Conclusions

The high temperature deformation behavior of 05Cr17Ni4Cu4Nb steel were investigated by hot compression test in the temperature range of 1000-1200°C, strain rate range of 0.01-10 s⁻¹ and strain range of 0-0.9. The main conclusions can be obtained as follows:

(1) The flow stress of 05Cr17Ni4Cu4Nb steel during hot compressive process decreases with increasing deformation temperature and decreasing strain rate.

(2) Microstructural observation confirms the occurrence of DRX behavior and the dynamic recrystallization grain size decreases with decreasing deformation temperature and increasing strain rate.

(3) The constitutive equation were established with material constants expressed by a fourth order polynomial fitting of strain to describe the influences of temperature, strain rate and strain on high temperature deformation behaviors of 05Cr17Ni4Cu4Nb steel.

References


