Flow Stress Constitutive Model of Ultra Low Carbon Steel in Warm Deformation

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Warm rolling technique of ultra low carbon steels is a new technology for metal forming. In order to study the flow stress of ultra low carbon steels in warm deformation, experiments of warm deformation of this grade were carried out on a hot simulation machine with the deformation temperature of 750 to 950°C, and strain rate of 1 to 70 s⁻¹. The experimental results have shown that the variation of flow stress with temperature in warm deformation is different from that in austenite deformation under high temperature, although the influences of strain rate and strain on flow stress in warm deformation of ULC steels are similar to those in austenite high temperature forming. A new flow stress constitutive model suitable to ferrite deformation of ultra low carbon steel is deduced in the paper on the basis of theoretical analysis and an actual flow stress model for ULC steels is obtained on the basis of experimental results. The comparisons between prediction values of new model and test values have proven that the new flow stress constitutive models given in the paper have higher precision when they are used to describe the flow stress variations of ULC in warm deformation.

KEY WORDS: ultra low carbon steel; warming deformation; flow stress; constitutive model.

1. Experiment Material and Experiment Method

The material used in this study is a kind of ULC steel provided by WISCO (Wuhan Iron and Steel Company, China) and was taken after roughing in hot strip continuous mill, WISCO. The chemical compositions are as follows (in wt%): 0.009C, 0.120Mn, 0.010S, 0.011P, 0.016Si, 0.040Cu and 0.027Al. The specimens were machined to cylindrical samples with dimension of \(\Phi 8 \times 12\) mm. Single pass tests were conducted on THERMECMASTEOR_Z simulation machine according to different deformation parameters. The lubricant of a special kind of glass powder was used in the tests in order to reduce the influence of friction. The accuracy of stress measurement in the tests is \(\pm 1\%\). Two specimens were used for one test. The experiment temperature was respectively 750, 800, 850, 900 and 950°C and deformation rate was respectively 1, 10, 40 and 70 s⁻¹. Deformation parameters, such as stress and strain, were sampled by computer.

2. Experiment Results and Discussion

Some of stress and strain curves of ULC steel in different deformation temperature and strain rate are shown in Figs. 1 to 3. Stress and strain curves in the condition of constant temperature and different strain rate are given in Fig. 1, from which we can see that flow stress increases with the increasing of strain rate. The stress and strain curves in Fig. 2 representing the effect of strain on stress at different temperature and constant strain rate have the characteristic of workhardening. Therefore, the influence rules of strain and strain rate on stress in ferrite forming condition are similar to those in austenite range.

The flow stress variations with temperature in constant strain rate and strain are given in Fig. 3. It is shown in Fig. 3 that flow stress decreased between 800 and 900°C in ferrite forming, which is different from the flow stress varia-
tion in single austenite range. The flow stress can be described by existing conventional stress equations in single austenite range at elevated temperature and single ferrite region at low temperature. It can be seen from iron and carbon equilibrium transformation diagram that the temperature range of lower flow stress is corresponding to the transformation temperature of austenite to ferrite. The lower flow stress is caused by ferrite phase because yield stress of ferrite phase is lower than that of austenite phase. The flow stress variation in two phase region is the comprehensive result of temperature effect and transformation effect. The particular variation rule of flow stress with temperature in two phases region is similar to the results of other researches, but these research works didn’t give the flow stress constitutive model suitable to deformation condition in two phases region. The existing flow stress equations used to describe the flow stress in austenite range cannot be used in the condition of ferrite deformation because the influence rules of temperature on flow stress are different in two deformation conditions. Thus it is necessary to put forward a new flow stress constitutive model to describe the flow stress variation in ferrite deformation condition.

3. Flow Stress Constitutive Model

Flow stress is the function of deformation temperature, strain and strain rate in conventional austenite processing region and it has the following form:

$$\sigma_S = A_0 \varepsilon \dot{\varepsilon}^2 \exp \left( \frac{A_1}{T} \right)$$ ...................(1)

where $\varepsilon$ is strain, $\dot{\varepsilon}$ strain rate, $T$ deformation temperature and $A_0, A_1, A_2, A_3$ model coefficients.

Other authors have given other flow stress equations, which have the same configuration with Eq. (1). So far there have been very few results about flow stress constitutive models in ferrite and austenite two phase region. Literature 4) used Eq. (1) to describe flow stress of ULC IF steel by modifying coefficients in equation.

Flow stress of steel is comprehensive reflection of softening and workhardening in steel during deformation. Thus flow stress of steel can be represented by Eq. (2):

$$\sigma_S = \sigma_0 + b_3 \varepsilon^b - \Delta \sigma_a$$ .................(2)

where $\sigma_0$ is initial flow stress which is related to deformation temperature and strain rate, and takes the form of Eq. (3); $\Delta \sigma_a$ represents the influence of ferrite phase on flow stress; $b_3, b_4, b_5, b_6$ are model coefficients.

$$\sigma_0 = b_1 Z b_2$$ .........................(3)

where $b_1, b_2$ are coefficients and $Z$ is Zener–Hollomon parameter, taking the form of Eq. (4):

$$Z = \dot{\varepsilon} \exp \left( \frac{Q_{\text{def}}}{RT} \right)$$ ......................(4)

where $Q_{\text{def}}$ is deformation activation energy and $R$ gas constant.

$\Delta \sigma_a$ is proportional to strain and time, in inverse proportion to deformation temperature, that is:

$$\Delta \sigma_a \propto \frac{b_3 \varepsilon^b}{T}$$ .......................(5)

Substituting $t=\varepsilon/\dot{\varepsilon}$ in Eq. (5), we get:

$$\Delta \sigma_a = b_3 \frac{\varepsilon^b}{T \dot{\varepsilon}^b}$$ .........................(6)

By substituting Eqs. (4) and (5) in Eq. (6), a new flow stress constitutive model is obtained in model (7):

$$\sigma_S = b_3 \left( \dot{\varepsilon} \exp \left( \frac{Q_{\text{def}}}{RT} \right) \right)^{b_5} + b_4 \varepsilon^b - b_6 \frac{\varepsilon^b}{T \dot{\varepsilon}^b}$$ ...............(7)

Equation (7) is flow stress constitutive model considering the effects of such factors as softening of ferrite phase in two phase region. Model (7) reflects the physical essential
of flow stress in ferrite deformation. The coefficients in model should be decided through experiments.

4. Establishment of Flow Stress Constitutive Model of ULC Steel

According to experiment results in this study, flow stresses in warm rolling condition were dealt with in two sections, i.e., low temperature section in single ferrite phase and ferrite and austenite two phase section. The conventional flow stress Eq. (1) in single austenite range is used to describe flow stress in former section and new flow stress constitutive model (7) given in this paper is used to represent the flow stress variation rule in later section. Flow stress models in two sections were obtained by nonlinear regression method and following flow stress constitutive models of ULC IF steel in ferrite deformation condition were established:

\[ \sigma_s = 0.46\dot{\varepsilon}^{0.115} \varepsilon^{0.08} \exp \left( \frac{6.0}{T} \right) \] ........................(8)

\[ \sigma_s = 2.56Z^{0.0771} + 217.02\dot{\varepsilon}^{0.5663} - 176.87 \frac{\varepsilon^{0.9552}}{T\dot{\varepsilon}^{0.1397}} \] ....(9)

\[ Z = \dot{\varepsilon} \exp \left( \frac{42117}{RT} \right) \]

Regression correlation coefficients of models (8) and (9) are respectively 0.9621 and 0.9446. The comparisons between calculated stress–strain curves based on the constitutive model with the experiment ones are shown in Figs. 1 to 3 as scattered points. It can be seen that the models proposed in the paper have higher precision and the prediction errors of two models are less than 6%. Therefore, the models are valid and can be used to calculate the flow stresses of ULC in warm deformation. Equation (8) is suitable to the temperature of lower than 800°C in single ferrite range and model (9) is applicable in the temperature range from 800 to 900°C.

5. Conclusion

(1) The influences of strain rate and strain on flow stress in warm deformation of ULC steel are similar to those in austenite high temperature forming. But the influences of temperature on flow stress in two different deformation conditions show different characteristics.

(2) Flow stress should be dealt with in two sections under condition of warm deformation and existing flow stress model configuration in austenite range can be used in low temperature section of single ferrite phase.

(3) A new flow stress constitutive model is given in this paper. The new model reflects the physical essential of flow stress variations in warm deformation condition and can be used to describe the flow stress variation rule in ferrite and austenite two phase region.

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