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HIGH TEMPERATURE CONSTITUTIVE MODEL OF Q345B STEEL

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In order to accurately predict the flow stress of Q345B steel at high temperature, the Q345B steel was subjected to a hot compression test on the Gleeble-1500D thermal simulation test machine at a deformation temperature of 1 173,15~1 373,15 K and a strain rate of 0,01~10 s^{-1}. Through the obtained true stress-strain curve, strain factors are introduced into the Arrhenius equation to establish a more accurate strain-coupled constitutive model. The results show that the correlation coefficient of the Arrhenius model considering strain compensation is 0,993, and the average absolute error is 4,59 %, which can accurately predict the flow stress. The experimental data and the calculated prediction curve fit well, which verifies the feasibility of the model.

Keywords: Q345B; thermal compression test; stress-stain curves; temperature; constitutive mode

INTRODUCTION

High-temperature deformation flow stress is one of the basic properties of materials. It is extremely important whether it is in formulating a reasonable hot processing technology or in the research of plastic deformation theory [1]. The constitutive equation is a mathematical model that reflects the stress, strain, and deformation parameters of a deformed material, and is the link between the flow stress of the material and its deformation degeneration parameters. In addition, it can accurately analyze the complex deformation behavior of materials in the heat treatment process, and its accurate flow stress value is the key to improve the calculation accuracy [2]. Although Q345B steel has been widely used in life, there is a lack of constitutive analysis for the rheological behavior of Q345B steel at high temperatures, and there is no accurate constitutive model, which limits the application of Q345B steel in industry. Therefore, it is full of great practical significance to construct a constitutive model that can accurately predict the flow stress in the full strain range.

The strain-compensated Arrhenius constitutive model introduces Z parameter into the constitutive model, so that the Arrhenius model can maintain high accuracy in the prediction of flow stress at high temperature under various complicated deformation conditions [3-5].

In order to study the rheological properties of Q345B steel, hot compression tests were carried out.

The Arrhenius constitutive model of strain compensation was established, and the experimental data and model prediction data were compared to verify the accuracy and feasibility of the constitutive model.

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EXPERIMENTAL MATERIALS AND TECHNOLOGY

Q345B steel is a carbon alloy steel with good comprehensive properties and has been widely used in such fields as bridges, vehicles, ships, buildings, pressure vessels. The chemical compositions of Q345B steel are 0,16 % C, 0,53% Si, 1,53 % Mn, 0,024 % P, 0,023 % S.

Isothermal compression tests were conducted under different conditions by a Gleeble-1500 simulator, and parameters such as displacement and stress were measured and recorded. The experimental temperature was set as 1 173,15 K, 1 273,15K, 1 373,15 K, 1 323,15 K, 1 373,15 K and the strain rate was set as 0,01 s^{-1}, 0,1 s^{-1}, 1 s^{-1} and 10 s^{-1}. The sample was heated to the deformation temperature at a rate of 10 K/s, kept warm for 3 minutes, and then proceeded with isothermal compression.

EXPERIMENTAL DATA AND CONSTITUTIVE MODEL ESTABLISHMENT

Figure 1 shows the true stress-strain curves of Q345B steel at different temperatures. It can be seen from the figure that at a certain temperature, the flow stress will increase as the strain rate increases. With the increase of strain, there are two types of flow stress: one is that it increases first and then tends to be gentle, that is, the dynamic recovery type; the other is to increase first, followed by a peak, and finally tends to be flat, that is, dynamic recrystallization. It can be clearly seen from the figure that the higher the temperature grows, the lower the strain rate tends to be, and the easier it is for dynamic recrystallization to occur.

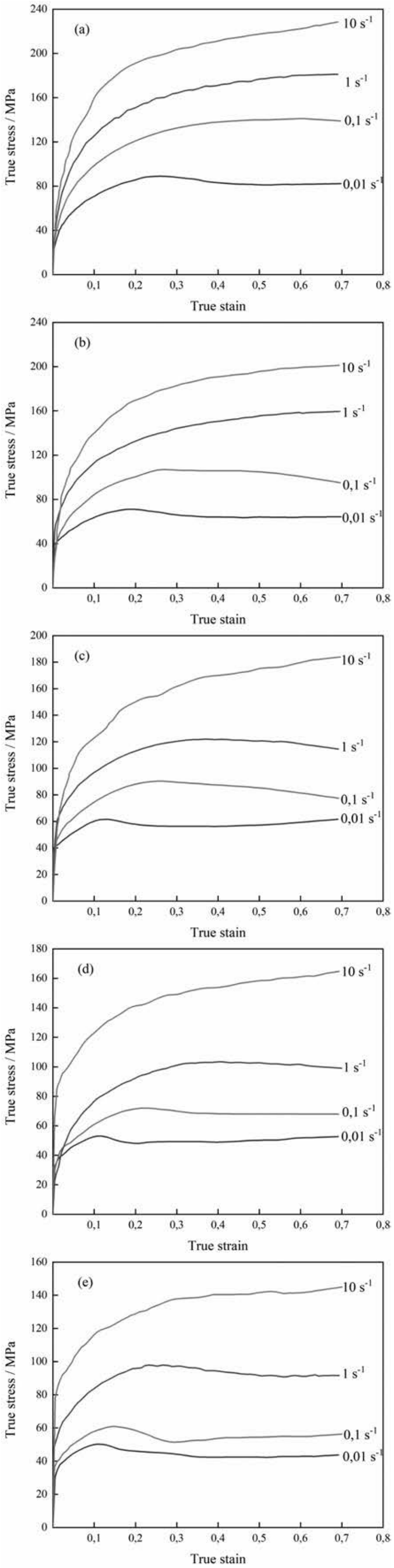

Figure 1 Stress-strain curves of Q345B at different temperature: (a) 900 °C; (b) 950 °C (c); 1 000 °C; (d) 1 050 °C; (e) 1 100 °C

The flow stress of metal during hot forming is mainly affected by the element composition and deformation parameters of metal [6]. The composition of a metal is constant during the thermal deform. Deformation parameters can be expressed by hyperbolic sine function:

$$\dot{\varepsilon} = f(\sigma)\exp(Q / RT) \qquad (1)$$

Different corresponding equations can be drawn upon According to the different stress levels:

1) At low stress levels ($\alpha\sigma < 0{,}8$), formula (1) can be simplified as:

$$\dot{\varepsilon} = A_1 \sigma^m \exp(-Q / RT) \qquad (2)$$

2) At high stress levels ($\alpha\sigma < 1{,}2$), formula (1) can be simplified as:

$$\dot{\varepsilon} = A_2 \exp(\beta\sigma)\exp(-Q / RT) \qquad (3)$$

3) At full stress levels, formula (1) can be simplified as:

$$\dot{\varepsilon} = A\left[\sinh(\alpha\sigma)\right]^n \exp(-Q / RT) \qquad (4)$$

where: $\dot{\varepsilon}$-strain rate / s^{-1}; α, A, A_1, A_2-material constant / s^{-1}; σ-flow stress / MPa; R-molar gas constant / 8,314·mol^{-1}·K^{-1}; Q-Thermal deformation activation energy / J·mol^{-1}; T-absolute temperature / K; m, n-stress index.

At the same time, taking the logarithm of both sides of equation (2) and (3):

$$\ln\dot{\varepsilon} = m\ln\sigma + \ln A_1 - Q / RT \qquad (5)$$

$$\ln\dot{\varepsilon} = \beta\sigma + \ln A_2 - Q / RT \qquad (6)$$

The peak stress was substituted into the equation to obtain linear regression curves of $\ln\dot{\varepsilon} - \ln\sigma$ and $\ln\dot{\varepsilon} - \sigma$, where were shown in Figure 2 and Figure 3.

Obtain the values of m and β from the graph, m = 6,529, β = 0,057798. Then calculate the value of α, α = 0,00885.

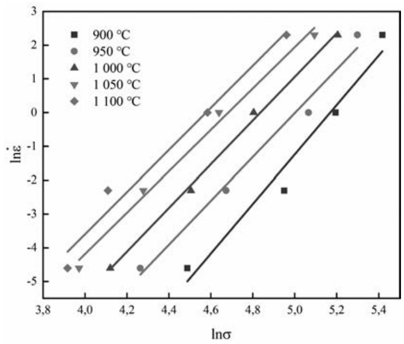

Figure 2 Relation curves of $\ln\dot{\varepsilon}$ and $\ln\sigma$

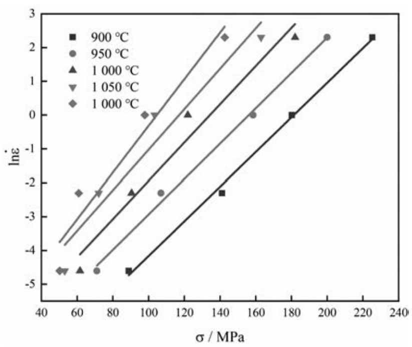

Figure 3 Relation curves of $\ln\dot{\varepsilon}$ and σ

Taking the logarithm of both sides of equation (4):

$$\ln \dot{\varepsilon} = \ln A + n \ln\left[\sinh(\alpha\sigma)\right] - Q / RT \tag{7}$$

It can be seen that when the temperature is constant, $\ln \dot{\varepsilon}$ and $\ln\left[\sinh(\alpha\sigma)\right]$ show a certain linear relationship:

$$n = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln\left[\sinh(\alpha\sigma)\right]} \tag{8}$$

Similarly, when the strain rate is constant, $\ln\left[\sinh(\alpha\sigma)\right]$ and 1/T have a certain linear relationship:

$$\frac{Q}{nR} = \frac{\partial \ln\left[\sinh(\alpha\sigma)\right]}{\partial(1/T)} \tag{9}$$

Bring the data into the formula and perform linear fitting regression on it to obtain the $\ln \dot{\varepsilon} - \ln\left[\sinh(\alpha\sigma)\right]$ and $\ln\left[\sinh(\alpha\sigma)\right] - 1\,000 / \mathrm{T}$ linear regression curves, where were shown in Figure 4 and Figure 5.

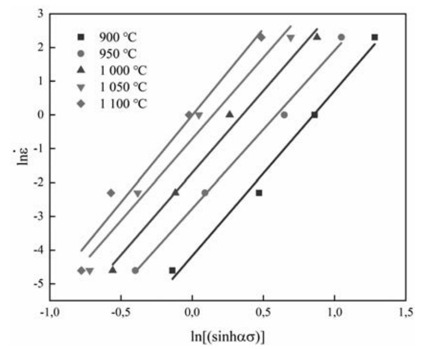

Figure 4 Relation curves of $\ln \dot{\varepsilon}$ and $\ln\left[\sinh(\alpha\sigma)\right]$

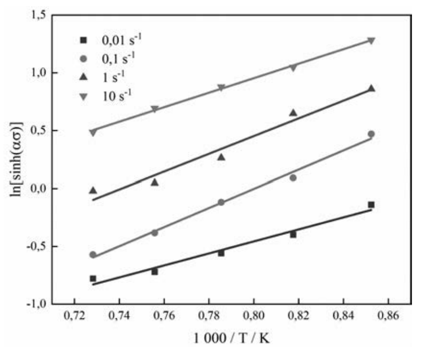

Figure 5 Relation curves of $\ln\left[\sinh(\alpha\sigma)\right]$ and $1000 / T$

The values of n and Q / nR can be obtained from the figure, n = 4,883, Q / nR = 6,845, and then bring in the values of n and R to get Q = 277 822,97 J/mol.

Using Zener-Hollomon parameters to describe the relationship between stress, strain rate and deformation temperature is:

$$Z = \dot{\varepsilon} \exp(Q / RT) = A\left[\sinh(\alpha\sigma)\right]^{n} \tag{10}$$

$$\ln Z = \ln A + n \ln\left[\sinh(\alpha\sigma)\right] \tag{11}$$

Fit the data points to obtain the linear regression curve of $\ln Z - \ln\left[\sinh(\alpha\sigma)\right]$, as is shown in Figure 6.

Obtain the value of intercept as ln A from the Figure 6, ln A = 24,43402, Then $A = 4,088 \times 10^{10}$.

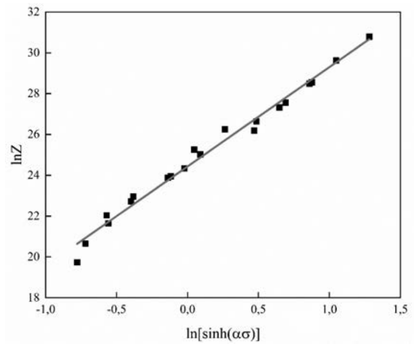

Figure 6 Relation curves of $\ln Z$ and $\ln\left[\sinh(\alpha\sigma)\right]$

Finally, the calculated values of A, α, Q and n are brought into equation (4) to obtain the peak stress constitutive equation of Q345B.

$$\dot{\varepsilon} = 4,088 \times 10^{10}\left[\sinh(0,00885\sigma)\right]^{4,883} \exp\left(-\frac{277\,822,969}{8,314T}\right) \tag{12}$$

SIMULATION PREDICTION AND VERIFICATION OF CONSTITUTIVE MODEL

In order to improve the accuracy of the equation prediction, strain factor is introduced into the Arrhenius equation to establish a more accurate strain-coupled constitutive model. A, α, Q and n under different strains can be calculated by substituting them into Formula (13), and the flow stress values under different strain rates can be obtained. The predicted values obtained were compared with experimental data, as is shown in Figure 7.

$$\sigma = \frac{1}{\alpha} \ln\left\{\left(\frac{Z}{A}\right)^{\frac{1}{n}} + \left[\left(\frac{Z}{A}\right)^{\frac{2}{n}} + 1\right]^{\frac{1}{2}}\right\} \tag{13}$$

It can be seen from Figure 7 that the experimental value and the predicted value are in good agreement, indicating that the strain-coupled Arrhenius constitutive model has high prediction accuracy. In order to explain the prediction accuracy of the equation more accurately, the correlation coefficient (R) and the average absolute error AARE / % are used to further verify its and prediction ability.

$$R = \frac{\sum_{i=1}^{n}\left(E_i - \bar{E}\right)\left(P_i - \bar{P}\right)}{\sqrt{\sum_{i=1}^{n}\left(E_i - \bar{E}\right)^{2}\left(P_i - \bar{P}\right)^{2}}} \tag{14}$$

$$AARE / \% = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{E_i - P_i}{E_i}\right| \times 100\,\% \tag{15}$$

Where, E_i is the experiment value; P_i is the predicted value; $\bar{E}$ and $\bar{P}$ are the average of the experimental values and the predicted values respectively; N is the number of samples.

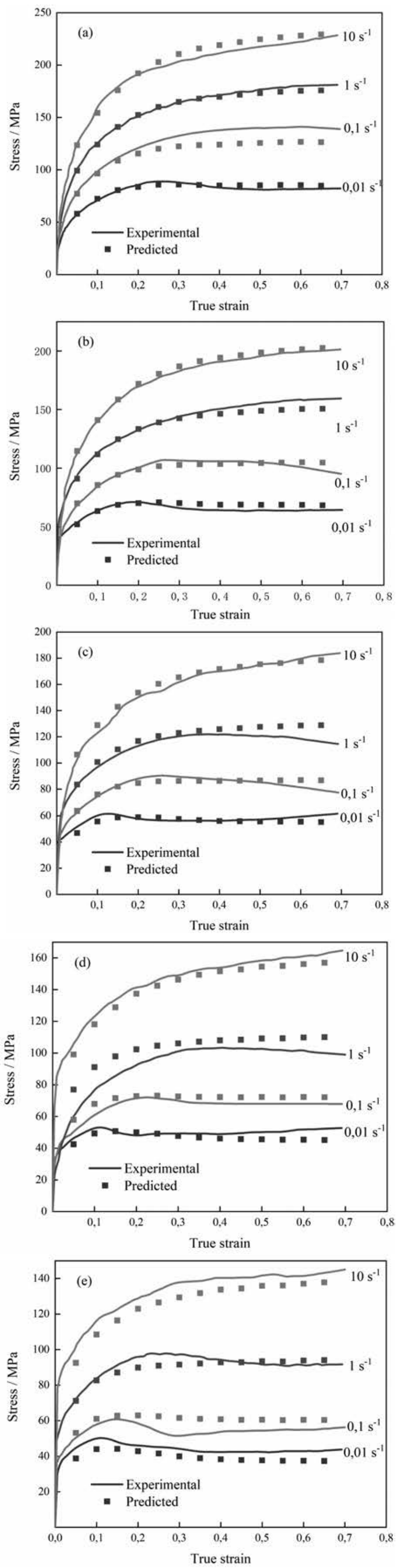

Figure 7 Comparison of predicted value and experimental value. (a) 900 °C; (b) 950 °C; (c) 1 000 °C; (d) 1 050 °C; (e) 1 100 °C.

It can be seen from Figure 8 that the experimental data and the flow stress predicted by the model have a good correlation: the correlation coefficient (R) value is

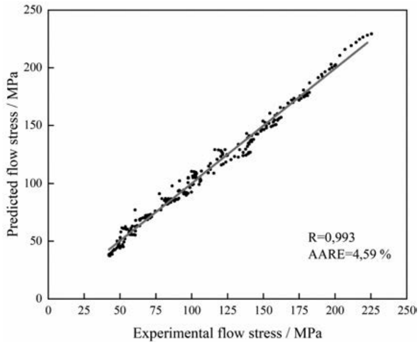

Figure 8 Correlation test between predicted value and experimental value

0,993, and the AARE / % value 4,59 %. This shows that the Arrhenius-type constitutive model has high prediction accuracy for the flow stress of Q345B steel.

CONCLUSION

The paper conducted a research on the constitutive relationship of Q345B steel at different temperatures and different strain rates. By introducing strain compensation factors, an Arrhenius constitutive model of Q345B steel within the desired strain range is established. The accuracy and feasibility of predicting flow stress are analyzed and verified. The results show that the constitutive model established in this paper has high accuracy.

Acknowledgments

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Note: The responsible translator for English language is T. K. Li -North China University of Science and Technology, China