Study on the constitutive equation of hot forming of boron steel sheet

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Abstract. The high temperature constitutive equation of boron steel sheet can describe the relationship of the thermodynamic parameters on the hot forming process of boron steel sheet. It can reflect the relationship between flow stress and strain, the temperature and strain rate, and is indispensable in the forming simulation of hot stamping forming process. In this paper, around the ultra-high-strength boron steel sheet 22MnB5, conduct thermodynamic tensile test on it. And the high-temperature constitutive equation of the high-strength steel sheet under the high-temperature austenite state is established according to the deformation theory. Finally, it is confirmed that the improved Norton-Hoff constitutive equation fitted with the experimental results is in good agreement with the flow stress relationship of boron steel 22MnB5.

1. Introduction

The hot stamping process of boron steel sheet needs to be predicted and optimized by finite element simulation technology. The high temperature constitutive equation of boron steel sheet can describe the relationship of the thermodynamic parameters of the boron steel sheet hot forming process. The constitutive equation is different for different materials, which directly affects the accuracy of finite element simulation.

Many scholars at home and abroad have studied the constitutive equation of metal materials. Because the hot forming process of boron steel plate is carried out at high temperature, and from a microscopic point of view, the temperature range is just within the austenite temperature range, it presents the state of austenite structure. The boron steel sheet under high temperature has the advantages of large plasticity, excellent ductility, low deformation resistance, large forming limit, small spring back, and the ability to form workpieces with complex geometric shapes. The flow stress is not only related to the strain of the steel sheet, but also related to the temperature of the sheet and its deformation rate. The thermodynamic model of boron steel sheet is indispensable in the hot stamping process, which can reflect the relationship between flow stress and strain, the temperature and strain rate. At present, from the published literature, there are few studies on the high-temperature constitutive equation of ultra-high strength boron steel. Among them, Naderi and Durrenberger [1] conducted isothermal unidirectional compression experiments on boron steel samples, and obtained the relationships between flow stress and strain, temperature and strain rate of samples at the temperature of 600 to 900 °C, and the deformation rate of the sample when the deformation rate of the sample is 0.1s⁻¹, 1s⁻¹, and 10s⁻¹, and the Voce-Kocks dynamic constitutive equation and the Molinari-Ravichandran phenomenological constitutive equation were used to describe the plastic deformation of boron steel. Liu and Xing et al. [2] established a flow
stress model for finite element simulation. Li Huiping, He Lianfang and others [3, 4] used the modified Arrhenius equation to describe the hot deformation behavior of boron steel sheet B1500HS in the high-temperature austenite state. The constitutive equation is

\[ \sigma = A \sinh (\alpha \varepsilon) \exp \left( -\frac{Q}{RT} \right) \]

Various high-temperature flow models have their own advantages and disadvantages. Starting from the feasibility of numerical simulation verification and parameter determination, the paper mainly chooses the improved Norton-Hoff constitutive equation when using the inverse forming finite element method to simulate hot forming [5, 6].

2. High temperature tensile test

2.1. Purpose

To study the basic mechanical properties of metal materials, a uniaxial tensile experiment is usually used. Through this experiment, the material properties such as yield strength, tensile strength, stiffness E, plasticity, and hardening index can be obtained, which can play an important role in the subsequent numerical simulation. The main goal is to study the performance of the boron steel sheet 22MnB5 in the high temperature forming stage, that is, the high temperature austenite stage, including: when the strain rate is constant, the flow curve of the boron steel 22MnB5 at different temperatures in the 900°C~600°C high temperature range, and the flow stress curve of boron steel when the strain rate is 0.01s⁻¹, 0.1s⁻¹, 1s⁻¹ at the same temperature.

2.2. Experimental program

(1) Fix the sample on the fixture of the simulation testing machine by mechanical clamping.

(2) Use resistance heating method to heat the sample, heat the small sample to 920°C and keep it for 5 minutes.

(3) Quickly cool the small sample to the set target temperature of 900°C, 800°C, 750°C, 700°C, 650°C, 600°C at a cooling rate of 50°C/s.

(4) Perform thermodynamic tensile experiments with different strain rates of 0.01s⁻¹, 0.1s⁻¹, and 1s⁻¹ at each designated temperature of 900°C~600°C.

(5) After stretching, cool the sample to room temperature at a rate greater than 30°C/s.

2.3. Purpose

Figure 1 is respectively the experimental results of the flow curves of the boron steel 22MnB5 at different temperatures in the high temperature range of 900°C to 600°C when the strain rate is 0.01s⁻¹, 0.1s⁻¹, and 1s⁻¹. It can be clearly seen that when the strain rate is constant, the higher the temperature, the lower the flow stress of the material.

In addition to the effect of temperature on the properties of boron steel, strain rate also has a great impact on material properties. Some scholars at home and abroad have also studied the effect of strain rate on the properties of hot stamping steel [7, 8]. It can be seen from the above figures1 that the flow stress of 22MnB5 is very different under the same temperature and different strain rates. To illustrate the effect of strain rate on the properties of boron steel more clearly, compare the flow stress of boron steel when the strain rate is 0.01s⁻¹, 0.1s⁻¹, and 1s⁻¹ at 750°C, as shown in Figure 2. It can be seen from that as the strain rate decreases, the flow stress of boron steel also decreases. The flow stress at a strain rate of 1s⁻¹ is about 3 times that of a strain rate of 0.01s⁻¹.

Because under the condition of constant temperature stretching, when the strain rate increases, it will drive more dislocations to move faster. As the dislocation density increases, macroscopically, it will show that the critical shear stress of the metal crystal becomes larger. And the deformation resistance is improved. At the same time, the increase of the strain rate will lead to a relatively slower softening rate due to dislocation climbing and dislocation reactions, and the time for dynamic recovery of boron steel is shortened, that is, the softening time becomes shorter, but the hardening process is relatively
intensified. Therefore, the critical shear stress of the metal becomes larger, and the steady-state flow stress becomes larger.

3. Constitutive equation establishment

Brosius and Karbasian et al. defined the modified Norton-Hoff equation, the formula is as follows:

\[
\begin{align*}
\sigma(\dot{\varepsilon}, \dot{T}) &= K (b + \dot{\varepsilon})^n \exp\left(\frac{\beta}{T}\right) \\
n(T) &= n_0 \exp(-c_n(T_i - T_0)) \\
m(T) &= m_0 \exp(-c_m(T_i - T_0))
\end{align*}
\]

(1)

In the above formula, \( K \) is Strength factor, \( b \) is Strain correction, \( \beta \) is Temperature Coefficient, \( c_n, c_m, n_0, m_0 \) is Relevant material parameters.

Using formula 2 to fit the high temperature rheological curve of 22MnB5, the relationship between the peak flow stress \( \sigma_p \) and the strain rate as shown in Figure 3 is obtained. It can be seen from that the flow stress peak values \( \sigma_p \) and \( ln(\frac{ds}{dt}) \) of 22MnB5 are linear at different temperatures.

\[
Q_{def} = \alpha \cdot R \cdot \left[ \frac{\partial \sigma_p}{\partial (\frac{1}{T})} \right|_{\dot{e}=\text{constant}} \right] = \left( \frac{\partial \ln\dot{T}}{\partial \sigma_p} \right|_{T=\text{constant}} \right) \cdot R \cdot \left[ \frac{\partial \sigma_p}{\partial (\frac{1}{T})} \right|_{\dot{e}=\text{constant}} \right]
\]

(2)

The high temperature deformation activation energy (283.6KJ/mol) of boron steel 22MnB5 can be obtained by further fitting based on experimental data. As shown in Figure 3, the parameter \( Z \) can be used to express the relationship between flow stress and strain, strain rate and temperature.
Combined with the improved Norton-Hoff constitutive equation, the relationship between the flow stress and strain, the temperature and strain rate of 22MnB5 boron steel in the high temperature austenite stage is further described. To make the numerical simulation more accurate and effective, the least square method polynomial is used to fit the nonlinear data to obtain the corresponding flow stress and hardening effect. Since a higher order may cause larger oscillations in the curve, starting from its accuracy, stability and calculation efficiency, a 5th-order polynomial is used to fit the parameters of Formula 1, namely:

$$\sigma = A\varepsilon^5 + B\varepsilon^4 + C\varepsilon^3 + D\varepsilon^2 + E\varepsilon + F \quad (3)$$

The parameters of the improved Norton-Hoff constitutive equation of the boron steel plate 22MnB5 are finally obtained by fitting. Except for $b$, $n_0$, other parameters at different temperatures are not constant values, and the parameter $\beta$ fluctuates greatly. Studies have shown that even if the variance of other parameters is small, a small disturbance will cause a large change in the high-temperature rheological curve. When fitting, the coefficient matrix obtained by using the least square method has symmetric positive definiteness, so the polynomial coefficients used in this paper are improved square root method. The interpolation formula and result are shown in formula 4.

$$P(x) = \sum_{j} \frac{y_j}{\prod_{i \neq j} (x - x_i)} \prod_{i} (x - x_i) \quad (4)$$

Parabolic interpolation can be used to solve the stress values corresponding to different strains at other temperatures. Figures 4 show that when the strain rate is $\dot{\varepsilon} = 0.1s^{-1}$ and $\dot{\varepsilon} = 1s^{-1}$, and the flow stress curves obtained by interpolation between experimental data and improved Norton-Hoff and Tong-Wahlen models at different temperatures. It can be seen from the two figures that the fitting results are very ideal, indicating that the two models are in good agreement with the flow stress relationship of boron steel 22MnB5.

Figure 3. Relationship between Flow stress peak $\sigma_p$, Strain rate of 22MnB5 and Z of 22MnB5

Figure 4. Comparisons of different model fitting result for 22MnB5 ($\dot{\varepsilon} = 0.1, \dot{\varepsilon} = 1$)
4. Conclusion
The high temperature constitutive relationship of boron steel plate is indispensable in the simulation of reverse forming in the hot stamping process, which can reflect the relationship between flow stress and strain, the temperature and strain rate. According to the deformation theory, the high-temperature constitutive equation of high-strength steel sheet in the high-temperature austenite state is established in the paper. Compare the experimental data at different temperatures and the flow stress curve obtained by the improved Norton-Hoff model interpolation, and it is confirmed that the improved Norton-Hoff constitutive equation fitted with the experimental results is in good agreement with the flow stress relationship of the boron steel 22MnB5.

Acknowledgments
This work was financially supported by the “Innovative and Strong School Project” scientific research project of the Education Department of Guangdong Province fund (2019KTSCX220).

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