Flow Stress Curve Modification and Constitutive Model of 20CrMoA Steel during Warm Deformation

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Received: 10 November 2020; Accepted: 26 November 2020; Published: 29 November 2020

Abstract: The warm deformation behavior of 20CrMoA steel at the temperature of 873–1123 K and the strain rate of 0.01–10 s−1 was investigated to obtain its processing property and optimum processing parameters. The true stress-true strain curves showed that flow stress reaches the peak rapidly, followed by slow decrease till reaching a steady state. This suggests a flow softening of dynamic recovery. The stress dropped with increasing deformation temperature and decreasing strain rate. The reduction became more distinct at lower temperature and higher strain rate due to flow softening caused by deformation heat. In the temperature range of 873–973 K, the deformation of 20CrMoA steel was more sensitive to temperature, and the average decline rate of steady stress was 6.9 times larger than that in the temperature range of 1023–1123 K. After modifying the stress curves, a constitutive model was developed for different deformation temperature ranges based on modified curves. The model was in good agreement with the experimental results.

Keywords: 20CrMoA steel; warm deformation; stress correction; constitutive model

1. Introduction

Warm forming generally refers to plastic deformation at a temperature of 873–1123 K, which combines the advantages of cold forming and hot forming. Warm forming parts have high precision, small tendency of oxidation and decarburization, and good feasibility for automatic production due to good formability [1,2].

Warm forming has been studied on various carbon steels. Abdollah-Zadeh proposed that continuous dynamic recrystallization was responsible for the ferrite grain refinement during warm deformation of a low carbon Nb-microalloyed steel [3]. Behrang found that the volume fraction of the DRX regions increased and grain size decreased as the carbon content of the alloy increased [4]. Rahul suggested that the recrystallization texture of ultra-low carbon steel was developed and influenced by deformation temperature after complete recrystallization [5]. Storojeva studied the microstructure evolution mechanism of medium carbon steel and found that the spheroidization of pearlite was accelerated due to the heavy warm deformation and the homogeneity of the cementite distribution and grain size depend on the cooling rate and deformation temperature [6]. Those works mainly focus on forming process and mechanism of grain refinement [7]. Application of warm forming has been conducted in industry such as multi-stage steel forging [8], precise forging of bevel gears [9], parts of aluminum alloys [10,11], and warm extrusion [12]. Recently, some have taken a closer look at warm cross wedge rolling (WCWR) [13–15], and the influence of rolling temperature on WCWR was argued. Huang et al. [16] carried on comparative study of warm and hot cross-wedge rolling and proposed that it is indefinite whether the decrease of energy consumption for heating workpiece can compensate the increase of the torque during warm rolling. Bulzak et al. [17] suggested
that over 80% of energy during warm and hot rolling was used to heat the billet, according to the comparative analysis of WCWR of ball pins at the rolling temperature 923 K, 1023 K, and 1273 K, which indicated that WCWR can save energy consumption. Huang investigated WCWR of 42CrMo at the ferrite region (rolling temperature of 923 K and 973 K) and did not give analysis of ferrite-austenite region. Bulzak analyzed WCWR of C45 steel at the ferrite region (923 K) and ferrite-austenite (1023 K), but the same constitutive equation and materials constants were applied at the different rolling temperature. Obviously, forming temperature is the focus on WCWR and directly determines the energy consumption during WCWR and the microstructure of products. Therefore, the appropriate constitutive model is the basis of simulation and application of WCWR. However, there are only a few studies regarding the constitutive model for warm forming. For example, Johnson-Cook model was employed to model the flow stress behavior of 20CrMnTiH from 873 K to 1123 K [18], in which stress error caused by deformation heat was not considered. The constitutive relationship of medium carbon steel was developed by the modified Arrhenius model based on Zener-Hollomon parameters at the deformation temperature varying from 823 K to 973 K [19], so it is only applicable to single-phase structure in low-temperature regions. The same method applied to 42CrMo steel as well [20]. Rastegari suggested that Arrhenius-type constitutive equation predicts the softening behavior of the dynamic spheroidization better than Johnson-Cook models and is more accurate [21].

The isothermal flow stress data are essential for the constitutive model [22,23]. When the strain rate is higher than a certain value, the actual temperature of the specimen may rise due to plastic deformation heat [24]. Therefore, it is necessary to modify the stress curves affected by deformation heat, especially under the forming conditions of low temperature and high strain rate. In addition, phase transformation is inevitable in warm forming, which will have a great influence on flow behavior. Therefore, the constitutive model of single-phase material does not apply to multi-phase materials [25].

In this study of WCWR, a low carbon and low alloy steel 20CrMoA was selected to investigate its warm deformation behavior by compression tests, which can establish a foundation for WCWR of shaft parts. It has high quenching ability, good machinability and cold strain plasticity [26]. This paper aims to analyze the influence of deformation temperature on the flow stress during warm deformation and determine proper process parameters. The sensitivity to various temperature ranges of the selected material was analyzed and the suitable forming temperature is suggested, then a constitutive model is developed based on modified flow stress and strain compensation. The validity and accuracy of results predicted by the proposed model is also investigated by comparing with the experimental curves.

2. Materials and Experimental Procedure

The chemical composition of 20CrMoA steel was: 0.2%C, 0.24%Si, 0.52%Mn, 0.92%Cr, and 0.16%Mo and the balance was for Fe. Figure 1 shows the original microstructure of 20CrMoA steel, which is ferrite and pearlite. JMatPro (Version 7.0, Sente Software Ltd., Guildford, Surrey, UK) is used for calculating the AC1 temperature which was 1004 K. The cylindrical specimens with a diameter of 8 mm and a height of 12 mm sampled from a homogenized bar were compressed on a Gleeble-3500 thermal simulator (Dynamic Systems Inc., Poestenkill, NY, USA). To reduce the friction between the specimens and dies during the tests, the two ends of the specimens were coated with the graphite lubricant. In this experiment, the deformation temperature was 873, 923, 973, 1023, and 1123 K. The curve of compression process is shown in Figure 2. First, each specimen was heated to the specified deformation temperature at a rate of 10 K/s and held for 3 min under isothermal conditions for heat balance. Then, the specimen was compressed in the axial direction at strain rates of 0.01, 0.1, 1, and 10 s⁻¹. The reduction in height was 65% at the end of the test (true strain is about 1.05). Finally, the specimens were immediately quenched in water after compression ended. During the experiment, the machine automatically collects data of true stress, true strain, and actual temperature of specimen.
3. Results and Discussion

3.1. Analysis of Stress–Strain Curves

Figure 3 shows the true stress-true strain curves of 20CrMoA steel at deformation temperature of 873–1123 K and deformation rate of 0.01–10 s\(^{-1}\), and the curves are not revised. In the early stage of warm deformation, the true stresses increased sharply and reached a peak, then decreased slowly until reaching a steady state, which was similar to the previously reported results that the stress increased with the decreasing deformation temperature and the increasing strain rate. However, different from the dynamic recrystallization during hot forming, the flow stress curves of warm forming mainly present dynamic recovery. It is worth noting that the stresses have drastic varieties in low temperature region (873–973 K), but slight changes in high temperature region (1023–1123 K) at a constant strain rate, which indicates that the deformation is more sensitive to the deformation temperature in low temperature range than in high one.
Figure 3. True flow stress-strain curves at different deformation conditions: (a) 0.01 s\(^{-1}\), (b) 0.1 s\(^{-1}\), (c) 1 s\(^{-1}\), (d) 10 s\(^{-1}\).

3.2. Effect of Deformation Energy on Temperature

Comparing Figure 3c with Figure 3b, it is worth noting that the effect of strain rate on stress is not significant. When the deformation temperature is 873 K, the peak stress (482.59 MPa) at strain rate of 1 s\(^{-1}\) is less than the value (490.06 MPa) at strain rate of 0.1 s\(^{-1}\). When the deformation temperature is 923 K, the peak stress (398.68 MPa) at strain rate of 1 s\(^{-1}\) is only 5.12% larger than the value (379.56 MPa) at strain rate of 0.1 s\(^{-1}\). In addition, as can be seen from Figure 3d, under the condition of lower deformation temperature and higher strain rate, the flow stress does not show a typical stable stage, but shows additional flow softening. The main reason is that rising deformation temperature affected the flow stress of metal and alloy. In the forming process, most of the energy is converted into heat energy, and enough deformation time can be provided for deformation at a low strain rate, enabling the heat caused by plastic work to dissipate to the surrounding environment [27,28]. Owing to the significant reduction in forming time at a high strain rate, most of the deformation heat cannot be dissipated timely but stored in the specimens as heat energy, thus resulting in the rising temperature and decreasing stress of the specimens. In other words, under the conditions of low temperature and high strain rate, the flow stresses collected in the tests are not the values at the preset temperatures, and as the specimen temperature rises, flow stress decreases, thus further softening.

According to the real-time temperature data collected by Gleeble-3500 simulator, the temperature of the specimen shows an upward trend. Figure 4a shows the temperature increments of the specimens under different strain rates at the temperature of 873 K, and the values increase with increasing strain rate and strain. However, the lower strain rate has less effect on the temperature of the specimen. If the strain rate is less than 0.1 s\(^{-1}\), the variation of temperature tends to zero which can be ignored. Figure 4b shows the variation of temperature increments of the specimens at the strain rate of 10 s\(^{-1}\) and in the low deformation temperature range. When the deformation temperature is 873 K, the temperature increment is the largest, and the temperature increment at a strain of 0.8 is 48.06 K, making the
actual temperature of the specimen almost equal to the next preset temperature of 923 K. Therefore, under the forming condition of low temperature and high strain rate, due to the temperature rise of the specimen, the flow stress curve shows additional softening after peak. According to the temperature increment, deformation at low strain rates values less than 0.1 s\(^{-1}\) can be regarded as isothermal process, but it is adiabatic process at high strain rates of 1 s\(^{-1}\) and 10 s\(^{-1}\). Due to the short deformation time, the deformation heat causes the temperature of the specimen to increase sharply, so it is necessary to modify the stress curves according to the temperature increment.

4. Constitutive Model during Warm Deformation

4.1. Correction of Flow Stress Curve

The effect of temperature increment on flow stress can be expressed as [29]

\[
\Delta \sigma = \frac{Q}{n\alpha R} \left( \frac{1}{T} - \frac{1}{T + \Delta T} \right)
\]

(1)

where \(\Delta \sigma\) is the value of temperature increment on stress, \(Q\) is the activation energy of thermal deformation, \(n\) is the stress index, \(\alpha\) is the stress level parameter, which will be calculated later, \(R\) is the gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)), \(T\) is the experimental temperature (K), and \(\Delta T\) is the temperature increment.

Arrhenius equation is widely used to describe the relationship of strain rate, flow stress and temperature. The relationship between temperature and strain rate is expressed by the Zener Hollomon parameter [30,31], which is given as

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

(2)

\[
\dot{\varepsilon} = AF(\sigma) \exp\left(-\frac{Q}{RT}\right)
\]

(3)

\[
F(\sigma) = \begin{cases} 
\sigma^n & \text{for } a\sigma < 0.8 \\
\exp(b\sigma) & \text{for } a\sigma > 1.2 \\
\sinh(a\sigma)^n & \text{for all } \sigma 
\end{cases}
\]

(4)

where \(\dot{\varepsilon}\) is strain rate (s\(^{-1}\)), \(\sigma\) is flow stress (MPa), \(R\) is the universal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)) and \(Q\) is the activation energy (KJ mol\(^{-1}\) K\(^{-1}\)). \(T\) is the experimental temperature (K), \(A, \alpha, \beta, n_1\), and \(n\) are material constant, and \(\alpha = \beta/n_1\). Substituting the power low and exponential law of \(F(\sigma)\) into Equation (3), it gives

\[
\dot{\varepsilon} = A\sigma^{n_1} \exp\left(-\frac{Q}{RT}\right)
\]

(5)

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

(6)
The following equations are obtained by taking logarithms of Equations (5) and (6), respectively.

\[ \ln \dot{\varepsilon} = n_1 \ln \sigma + \ln A - \frac{Q}{RT} \]  
\[ \ln \dot{\varepsilon} = \beta \sigma + \ln A - \frac{Q}{RT} \]  

In terms of the low and high stress level, Equation (3) can be expressed as

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

Taking the logarithm of both sides of Equation (9), it gives

\[ \ln \dot{\varepsilon} = n \ln[\sinh(\alpha \sigma)] + \ln A - \frac{Q}{RT} \]  

Differentiating Equation (10), it gives

\[ n = \left\{ \frac{\partial (\ln \dot{\varepsilon})}{\partial (\ln[\sinh(\alpha \sigma)])} \right\}_T \]  
\[ Q = RnT \frac{\partial [\ln[\sinh(\alpha \sigma)]]}{\partial (1/T)} \]  

Substituting the peak stress to Equation (7), Equation (8), and Equation (10), the constants can be obtained: \( \beta = 0.0567, n_1 = 16.267, \alpha = 0.00348, n = 11.612, b = 5.536 \), then, \( Q = 534.53 \text{ kJ/mol} \).

Substituting \( \alpha, n, Q \) to Equation (1), the flow stress at 1 s\(^{-1}\) and 10 s\(^{-1}\) are corrected and the modified curve is shown in Figure 5. It can be seen from Figure 5 that under the condition of high strain rate, the increase of deformation temperature has a significant influence on the stress. The stress value is largely different at a lower temperature and a higher strain rate. Under the deformation condition of 873 K and 10 s\(^{-1}\), the maximum value of \( \Delta \sigma \) is 86.58 MPa, 18.8% higher than the measured value, while under the deformation condition of 1073 K and 1 s\(^{-1}\), the maximum value of \( \Delta \sigma \) is only 8.55 MPa, only 3.77% higher than the measured value. Under the deformation condition of 1123 K and 1 s\(^{-1}\), the stress error can be ignored due to the small temperature increment.

![Figure 5. Modified stress-strain curves: (a) 1 s\(^{-1}\) (b) 10 s\(^{-1}\).](image)

4.2. Construction of Constitutive Model

According to the modified flow stress data, the relationship between steady stress and temperature under various strains can be analyzed, as shown in Figure 6. It can be seen that the steady stress decreases with the increase of temperature, but the average rate of decline in low-temperature region
is 1.93, which is 6.89 times as much as the value 0.28 in the high-temperature region. Obviously, the deformation is more sensitive in the high temperature region. At a temperature lower than \( AC_1 \) temperature (1004 K), the microstructure of 20CrMoA steel is mainly ferrite, but austenite emerges caused by phase transformation in high temperature region. It has been widely recognized that the crystal lattice types of ferrite and austenite are body-centered cubic (BCC) and face-centered cubic (FCC), respectively. BCC metals are much less active than FCC metals, resulting in much higher thermal sensitivity [32]. It is the main reason that the steady stress decreases more rapidly in the low temperature region. Therefore, it is necessary to establish constitutive models of different temperature ranges according to different temperature sensitivities.

![Figure 6. Relationship between steady stress and temperature.](image)

Substituting the peak stresses of the modified curves to Equations (7)–(9) for variable linear regression, the experimental data obtained from the warm compression tests can be fitted into a series of straight lines as shown in Figures 7–9. Calculating the average value of the slope of the fitting line in the figures respectively, the material constants \( n_1, \beta, \eta, \) and \( Q \) can be obtained, as shown in Table 1.

![Figure 7. Relationship between stress and strain rate: (a) \( \ln \varepsilon \) and \( \sigma \) (b) \( \ln \varepsilon \) and \( \ln \sigma \).](image)

**Table 1. Material constants in Arrhenius equations (peak stress).**

| Low Temperature Region (873–973 K) | High Temperature Region (973–1123 K) |
|-----------------------------------|-------------------------------------|
| \( a_L \)                          | \( a_H \)                           |
| \( n_L \)                          | \( n_H \)                           |
| \( Q_L \) (J/mol-K)                | \( Q_H \) (J/mol-K)                 |
| \( \ln A_L \)                      | \( \ln A_H \)                       |
| 0.00246                           | 0.00519                             |
| 14.674                            | 6.948                               |
| 652.608                           | 150.821                             |
| 81.474                            | 14.45                               |
work hardening. Therefore, in order to more accurately estimate the plastic flow behavior of 20CrMoA steel, the strain compensation should be included in the constitutive model during warm deformation. In the strain range of 0–0.8, the material constants ($\alpha$, $n$, $A$, $Q$) of the constitutive equations under different true strains are calculated with an interval 0.05. These material constants can be expressed by the polynomial function of strain, as shown in Equation (13). Fitting the polynomials, the coefficients of functions can be obtained, as shown in Tables 2 and 3.

$$\alpha(\varepsilon) = B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3 + B_4\varepsilon^4 + B_5\varepsilon^5$$
$$n(\varepsilon) = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 + C_4\varepsilon^4 + C_5\varepsilon^5$$
$$Q(\varepsilon) = D_0 + D_1\varepsilon + D_2\varepsilon^2 + D_3\varepsilon^3 + D_4\varepsilon^4 + D_5\varepsilon^5$$
$$\ln A(\varepsilon) = E_0 + E_1\varepsilon + E_2\varepsilon^2 + E_3\varepsilon^3 + E_4\varepsilon^4 + E_5\varepsilon^5$$

(13)

Figure 8. Relationship between $\dot{\varepsilon}$ and $\ln(\sigma_{pl})$: (a) low temperature region, (b) high temperature region.

Figure 9. Relationship between $\ln\sinh(\alpha\sigma)$ and 1000/T at different strain rates.

4.3. Strain Correction for Constitutive Models

Obviously, the above equations do not consider the effect of strain on the calculation of material constants. The plastic flow behavior of 20CrMoA steel during warm forming is affected by strain which further significantly affects the forming time and the balance between dynamic softening and work hardening. Therefore, in order to more accurately estimate the plastic flow behavior of 20CrMoA steel, the strain compensation should be included in the constitutive model during warm deformation. In the strain range of 0–0.8, the material constants ($\alpha$, $n$, $A$, $Q$) of the constitutive equations under different true strains are calculated with an interval 0.05. These material constants can be expressed by the polynomial function of strain, as shown in Equation (13). Fitting the polynomials, the coefficients of functions can be obtained, as shown in Tables 2 and 3. Figure 10 shows the polynomial curves of material constants fitted in the low and high temperature region.
Table 2. Coefficients of the polynomial functions of $\beta$, $\alpha$, $n$, $Q$, and $\ln A$ (873–973 K).

| $\alpha$ | $n$ | $Q$ | $\ln A$ |
|----------|-----|-----|---------|
| $B_{10}$ | 0.00326 | $C_{L0}$ | 18.28 | $D_{L0}$ | 492.4 | $E_{L0}$ | 60.55 |
| $B_{11}$ | -0.00104 | $C_{L1}$ | -49.74 | $D_{L1}$ | 1886.2 | $E_{L1}$ | 256.68 |
| $B_{12}$ | 0.0504 | $C_{L2}$ | 290.1 | $D_{L2}$ | 7351.27 | $E_{L2}$ | -1044.27 |
| $B_{13}$ | -0.1148 | $C_{L3}$ | -810.97 | $D_{L3}$ | -11,406.17 | $E_{L3}$ | 1735.56 |
| $B_{14}$ | 0.1256 | $C_{L4}$ | 1017.3 | $D_{L4}$ | -6851.16 | $E_{L4}$ | -1204.69 |
| $B_{15}$ | -0.0525 | $C_{L5}$ | -413.81 | $D_{L5}$ | 957.75 | $E_{L5}$ | 256.26 |

Table 3. Coefficients of the polynomial functions of $\beta$, $\alpha$, $n$, $Q$, and $\ln A$ (1023–1123 K).

| $\alpha$ | $n$ | $Q$ | $\ln A$ |
|----------|-----|-----|---------|
| $B_{H0}$ | 0.0084 | $C_{H0}$ | 9.78 | $D_{H0}$ | 534.72 | $E_{H0}$ | 57.25 |
| $B_{H1}$ | -0.0344 | $C_{H1}$ | -31.57 | $D_{H1}$ | -3327.82 | $E_{H1}$ | -369.44 |
| $B_{H2}$ | 0.144 | $C_{H2}$ | 160.28 | $D_{H2}$ | 11,926.74 | $E_{H2}$ | 1322.67 |
| $B_{H3}$ | -0.2915 | $C_{H3}$ | -420.7 | $D_{H3}$ | -22,568.5 | $E_{H3}$ | -2516.77 |
| $B_{H4}$ | 0.2866 | $C_{H4}$ | 507.12 | $D_{H4}$ | 21,250.61 | $E_{H4}$ | 2393.33 |
| $B_{H5}$ | -0.1097 | $C_{H5}$ | -222.61 | $D_{H5}$ | -7749.15 | $E_{H5}$ | -882.89 |

![Figure 10](image)

Figure 10. Relationships between material constants $\alpha$, $n$, $Q$, and $\ln A$ and $\varepsilon$: (a) $\alpha$, (b) $n$, (c) $Q$, (d) $\ln A$.

Substituting the material constants into Equation (3), the constitutive model with strain correction of 20CrMoA steel during warm deformation can be obtained, as shown in Equation (14). According to the previous analysis, due to the different microstructures of the material, the material has higher temperature sensitivity in the ferrite region than in the dual phase region. Therefore, when deformation
temperature is lower than the transformation temperature (1004 K), the material constants of low temperature range can be applied, otherwise, that in high temperature range should be applied.

\[
\begin{align*}
\alpha(\varepsilon) & = B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3 + B_4\varepsilon^4 + B_5\varepsilon^5 \\
n(\varepsilon) & = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 + C_4\varepsilon^4 + C_5\varepsilon^5 \\
Q(\varepsilon) & = D_0 + D_1\varepsilon + D_2\varepsilon^2 + D_3\varepsilon^3 + D_4\varepsilon^4 + D_5\varepsilon^5 \\
\ln A(\varepsilon) & = E_0 + E_1\varepsilon + E_2\varepsilon^2 + E_3\varepsilon^3 + E_4\varepsilon^4 + E_5\varepsilon^5
\end{align*}
\]  

(14)

4.4. Verification of Constitutive Equation

In order to verify the constitutive model of 20CrMoA steel with strain correction, the fifth-degree polynomial coefficients in Tables 2 and 3 are respectively substituted into Equation (14), then the predicted stress values in low and high temperature regions are obtained. The predicted stress values with a strain variable of 0.1–0.8 at an interval of 0.05 are compared with those in experimental curves, as shown in Figure 11, which demonstrates that the predicted true stress values agree well with the experimental ones in the whole strain rate range.

![Figure 11. Comparison between experimental and predicted flow stresses.](image)

The correlation coefficient R and average absolute relative error (AARE) are used to evaluate the accuracy of the constitutive equation. The value of R reflects the degree of correlation of the predicted values and experimental ones in Equation (15). AARE calculated by comparing relative errors item by item, was used to measure predictability in Equation (16). Where, \(\bar{E}\) is the experimental stress, and \(\bar{P}\) is the predicted stress. \(\bar{E}\) and \(\bar{P}\) are the average values of \(E\) and \(P\), respectively. \(N\) is the number of data used for study.

\[
R = \frac{\sum_{i=1}^{N}(E_i - \bar{E})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{N}(E_i - \bar{E})^2 \sum_{i=1}^{N}(P_i - \bar{P})^2}}
\]  

(15)
Figure 12a shows that the correlation coefficient ($R^2$) between the predicted values and the experimental ones is 0.996, and the average absolute relative error (AARE) is 2.63%. In the sample data of predicted stress values, the maximum relative error is 9.04%, and the proportion of relative error between −5% and 5% is 86.9%, Figure 12b shows the statistical analysis of relative error and indicates that the constitutive model is highly accurate in predicting flow stress.

![Figure 12](image)

**Figure 12.** Error analysis and statistics of predicted stresses: (a) correlation between experimental and predicted flow stresses, (b) statistical analysis of relative error.

5. Conclusions

1) 20CrMoA steel has higher temperature sensitivity in the low temperature region (ferrite region). With increasing temperature, the decline rate of the steady-state stress is 6.9 times that of the high temperature range.

2) Considering the large flow stress at temperature less than 1023 K and the low temperature sensitivity at temperature more than 1023 K, it is suggested that the warm forming temperature of 20CrMoA steel should be above 1023 K. While the deformation resistance is relatively stable, the temperature can be adjusted appropriately to change the proportion of dual phase microstructure to achieve the expected mechanical properties. Further study on the microstructure is essential for more accurate forming temperature region.

3) According to the effect of temperature increment on stress, it is necessary to modify the flow stress curves under the condition of low temperature and high strain rate. Considering the great difference in the sensitivity of deformation to temperature, the hyperbolic sine constitutive model of 20CrMoA steel during warm deformation is established in both low and high temperature ranges. After strain correcting, the constitutive model can accurately predict the flow stress. The correlation coefficient $R^2$ between predicted values and experimental values is 0.996 and AARE is 2.63%.

**Author Contributions:** Conceptualization, S.X. and X.S.; methodology, S.X.; Software, S.X.; validation, S.X., J.C., and X.S.; formal analysis, S.X.; investigation, S.X.; resources, S.X.; data curation, S.X.; writing—original draft preparation, S.X.; writing—review and editing, S.X. and S.L.; visualization, S.X. and J.C.; supervision, S.L.; project administration, X.S.; funding acquisition, X.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China (grant no. 51975301), and the Natural Science Foundation of Zhejiang Province of China (grant no. LZ17E050001).

**Conflicts of Interest:** The authors declare no conflict of interest.
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