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A Modified Johnson-Cook Model for Hot Deformation Behavior of 35CrMo Steel

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Abstract: In this work, a compression experiment of 35CrMo steel is carried out over a wide range of temperatures (1123–1423 K) and strain rates ($0.1\text{--}10\text{ s}^{-1}$) to obtain further understandings of the flow behaviors. The results show that the strain hardening effect of 35CrMo steel is stronger than that of dynamic recrystallization at low temperature and high strain rate; on the contrary, the rheological curves show typical dynamic recrystallization characteristics at high temperature and low strain rate. This indicates that the strain hardening and recrystallization behavior of 35CrMo steel is affected by temperature, strain and strain rate, and its true stress-strain curves can be observed typical work hardening and dynamic softening features. A modified Johnson-Cook (JC) model is developed to predict the flow stress of the alloy. The results of the comparison show that the predicted values of the modified JC model are in good agreement with the experimental values.

Keywords: 35CrMo steel; constitutive equation; hot deformation; strain hardening

1. Introduction

35CrMo steel has been widely used in the manufacture of various large components and medium-sized parts, such as driveshafts, crankshafts, and fasteners, for its excellent characteristics of good wear, impact, fatigue, and corrosion resistance [1–5]. Service in the deep sea environment of the bearing part and rotary shaft, it is not only subjected to strong alternating loads, but also faces the cross-effect of various corrosion modes, and its corrosion resistance is directly related to the microstructure, which can be effectively controlled by a hot working process [6,7]. Therefore, in order to achieve the excellent properties of 35CrMo steel parts, it is necessary to study its hot deformation behavior in depth.

In order to effectively predict the high temperature flow stress of alloys and metals, researchers put forward different kinds of constitutive equation, which can be divided into phenomenological constitutive models, artificial neural network models, and physics-based models. Johnson-Cook (JC) model [8,9], Arrhenius model [10,11], and L-parameter compensation model [12] proposed by Lin et al., or modified models based on these models, are phenomenological classes. Among them, Arrhenius hyperbolic sine equation is one of the most commonly used constitutive models. In recent years, Arrhenius model and its modified equation were developed to predict the flow behaviors of cast A356 aluminum alloy [13], GCr15 steel [14], AISI 321 austenitic stainless steel [15], 21Cr economical duplex stainless steel [16], Inconel 600 superalloy [17], and 9Cr-1Mo steel [18]. Moreover, neural network models were used to predict the flow behaviors of 28CrMnMoV steel [19], glass fiber reinforced polymers [20], A356 aluminum alloy [21], and 42CrMo steel [22]. In addition, dynamic recrystallization (DRX) model [23], Zerilli-Amstrong (ZA) model [24,25], mechanical threshold stress plasticity (MTS) model [26], Cellular Automata (CA) model [27], and Bonder-Partom (BP) model [28] belong to the

physics-based models. The study of V-4Cr-4Ti [29], medium carbon and vanadium microalloyed steels [30], and Mg-Al-Zn alloy [31] shows that the constitutive equation based on microscopic mechanism has good applicability, which can be used to characterize the relationship between flow stress and microstructure during high-temperature rheological process.

However, these physics-based models, including the DRX model, ZA model, MTS model, and BP model, etc., are mainly based on dislocation theory and kinetics of slip. They always have complex forms and the practical applications are limited, for a large number of experimental data are needed. As one of the empirical models, JC model was widely used with simple expression and only five material constants, and the strain rate hardening and thermal softening effect are taken into account [32,33]. Considering the interaction of temperature, strain and strain rate on the alloys flow stress of 30Cr2Ni4MoV rotor steel and a typical high-strength alloy steel, Wang et al. [34] and Lin et al. [35] have made appropriate changes to the original JC model to describe the flow stress responses of the alloys under different hot deformation conditions. In the modified models, the JC model parameters are often expressed as a function of strain, strain rate, and temperature. For example, some modified JC models were improved to predict flow stresses of 20CrMo alloy steel [36], titanium matrix composites [37], and B1500HS boron steel [38]. Also, the improved JC model has been widely used in a variety of engineering applications, and embedded in a number of finite element software [39–41].

Although some materials have made progress in these constitutive models, there is no research on the JC model of 35CrMo steel in addition to the ZA model under high temperature dynamic compression tests [42,43], and it is unclear whether the existing constitutive model is suitable for describing the relationship between flow stress and hot deformation conditions. Therefore, it is necessary to further study the applicability of the JC model to 35CrMo steel within a certain temperature and strain rate range.

2. Experiments and Results

A commercial 35CrMo steel with the composition 0.34C–0.21Si–0.56Mn–0.95Cr–0.19Mo–0.0051S–0.019Si–(balance) Fe (wt %) was used in this investigation. Cylindrical specimens were machined with a diameter of 10 mm and a height of 12 mm. The compression tests were performed on a Gleeble 3810 thermo-simulation machine (Central South University, Changsha, China) in the temperatures range of 1123–1423 K at an interval of 100 K, while the imposed constant strain rates were 0.1, 1, and 10 s^{−1}. All specimens were heated up to 1523 K at a heating rate of 10 K/s by thermo-coupled feedback-controlled AC current, and held for 360 s, then cooled to the deformation temperature at a rate of 10 K/s. Prior to the compression test, the sample was held at the deformation temperature for 120 s to eliminate thermal gradients. The reduction in height was 60% at the end of the compression tests. In addition, it should be noted that tests at strain rates exceeding 1 s^{−1} will be adiabatic in nature [44]. Stress levels are high enough—even at the highest temperatures—to introduce adiabatic heating. Thus, temperatures will not be constant, and this effect was ignored in this experiment.

It can be seen from the Figure 1 that the true stress-strain curves of 35CrMo steel exhibit peak stresses at small strains, after them the flow stresses decrease monotonically until high strains, and finally stabilized, showing typical work hardening and dynamic softening features under different deformation conditions, respectively. The strain hardening effect of 35CrMo steel is stronger than the dynamic recrystallization softening effect when the temperature is low and the strain rate is high, and the flow stress increases with the increase of strain, such as in 1123 K/0.1 s^{−1} and 1323 K/10 s^{−1}. On the contrary, at high temperature and low strain rate, the stress increased rapidly to the peak after a slight decline, and followed by a steady state flow. This indicates that the strain hardening and recrystallization behavior of 35CrMo steel is affected by temperature, strain, and strain rate. Although the initial strain value of the curves entering the steady state rheological stage varies with the experimental conditions, most of the curves enter the steady stage after the true strain exceeds 0.25. This phenomenon is the result of dynamic equilibrium between work hardening and various softening mechanisms (dynamic recrystallization, dynamic recovery) [45,46]. As the JC model mainly describes

the relationship between flow stress and temperature, strain, and strain rate in the steady-state rheological stage. Therefore, we intercept the data in Figure 1 where the true strain in the range of 0.25 to 0.6 as the data source of the constitutive equation.

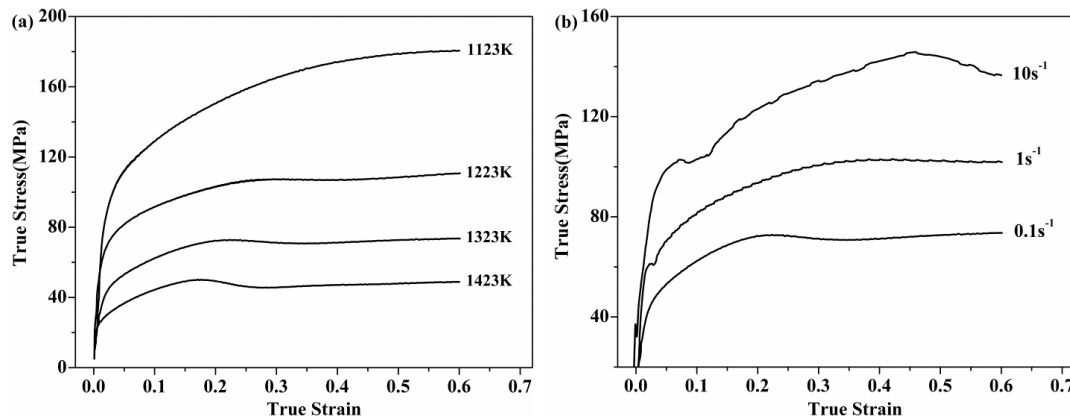


Figure 1. True stress-strain curves of 35CrMo steel; (a) strain rate $\dot{\epsilon} = 0.1 \text{ s}^{-1}$; (b) $T = 1323 \text{ K}$.

3. The Original JC Model and Its Modified Equation

The original JC model is a purely empirical model. It is well known as a strain, strain rate, and deformation temperature-dependent phenomenological flow stress model, which simple in form and have a clear physical interpretation. The form of original JC model [8,9] can be expressed as:

$$\sigma = (A + B\epsilon^n) \left(1 + C \ln \dot{\epsilon}^*\right) (1 - T^{*m}) \quad (1)$$

where σ is the Von Mises flow stress, MPa; A is the yield stress at reference strain rate and reference temperature, MPa; B is the coefficient of strain; ϵ is the equivalent plastic strain; n is the strain hardening exponent; C and m are the JC model parameters which represent the coefficient of strain rate sensitivity and thermal softening exponent, respectively. $\dot{\epsilon}^* = \dot{\epsilon}/\dot{\epsilon}_0$ is the dimensionless strain rate, $\dot{\epsilon}$ is the strain rate, s^{-1} ; $\dot{\epsilon}_0$ is the reference strain rate, s^{-1} . $T^* = (T - T_{\text{ref}})/(T_m - T_{\text{ref}})$ is the relative temperature, T is the absolute temperature, K; T_m is the melting temperature (1757 K for 35CrMo steel) and T_{ref} is the reference temperature, K.

In Equation (1), the first item $(A + B\epsilon^n)$ plays a leading role in the predicted result and determines the approximate range of stress. The $(1 + C \ln \dot{\epsilon}^*)$ of second item and $(1 - T^{*m})$ of third item at reference strain rate and reference temperature equal to 1, and do not affect the calculation results, but they will play an adjustment role in the calculation of flow stress when the temperature and strain rate deviate from the reference point. The strain rate sensitivity coefficient C and thermal softening exponent m determine the magnitude of the adjustment.

Compared with Arrhenius equation, JC constitutive equation has the characteristic of simple parameters. It is used to predict the rheological behavior of the material with little change in the flow stress after the peak stress, but the prediction effect is not ideal for the complex rheological behavior of those materials [35,47,48]. It is found that the second order polynomial can more accurately describe the relationship between flow stress and strain, rather than the original exponential expression. Furthermore, the item $(1 - T^{*m})$ can be rewritten as an exponential relationship between σ and $(T - T_{\text{ref}})$. Therefore, a modified JC model is proposed with the following form:

$$\sigma = \left(A_1 + B_1\epsilon + B_2\epsilon^2\right) \left(1 + C_0 \ln \dot{\epsilon}^*\right) \exp \left[\left(\lambda_1 + \lambda_2 \ln \dot{\epsilon}^*\right) (T - T_{\text{ref}}) \right] \quad (2)$$

where A_1 , B_1 , B_2 , C_0 , λ_1 , and λ_2 are the JC model parameters, the meanings of σ , ϵ , T , T_{ref} and $\dot{\epsilon}^*$ are the same as that of the original JC model.

4. Results and Discussion

4.1. The Modified JC Model

When the deformation conditions at reference temperature 1123 K and strain rate 0.1 s^{-1} , Equation (2) is transformed to:

$$\sigma = (A_1 + B_1\varepsilon + B_2\varepsilon^2) \quad (3)$$

Substitute stress and strain data (from 0.25 to 0.6) under the deformation conditions, the σ - ε curve can be obtained, and conduct two-order polynomial fitting. Then, the values of A_1 , B_1 , and B_2 can be fitted as 114.45 MPa, 227.75 MPa, and 197.47 MPa, respectively, as shown in Figure 2.

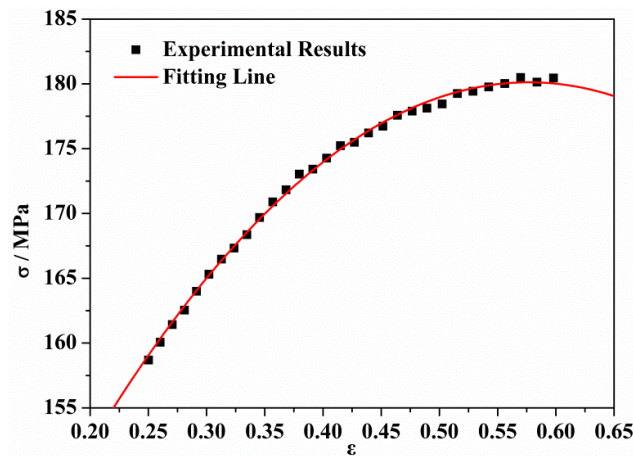


Figure 2. Relationship between σ and ε (1123 K/ 0.1 s^{-1}).

When the deformation temperature is 1123 K, Equation (2) can be rearranged to the following forms:

$$\frac{\sigma}{(A_1 + B_1\varepsilon + B_2\varepsilon^2)} = (1 + C_0 \ln \dot{\varepsilon}^*) \quad (4)$$

Substituting the three different strain rates and the corresponding flow stress at different strains (from 0.25 to 0.6 with the interval of 0.05, a total of eight strain values) into Equation (4), draw $\sigma/(A_1 + B_1\varepsilon + B_2\varepsilon^2)$ - $\ln \dot{\varepsilon}^*$ curve, and carry out linear fitting, as shown in Figure 3, one gets C_0 is the strain-dependent parameter, and $C_0 = C_0(\varepsilon)$. Then, parameter C_0 corresponds to the value of the different strains as shown in Table 1.

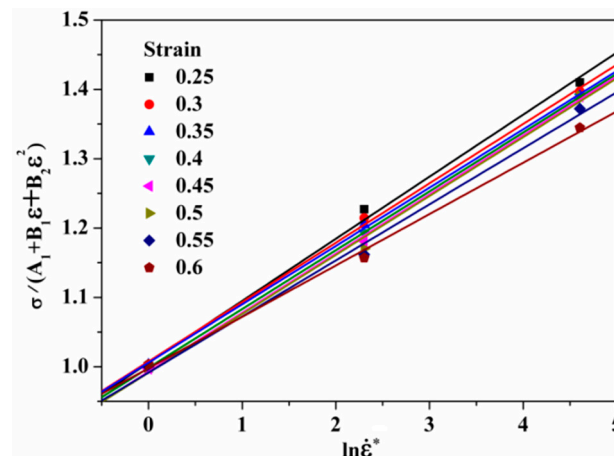
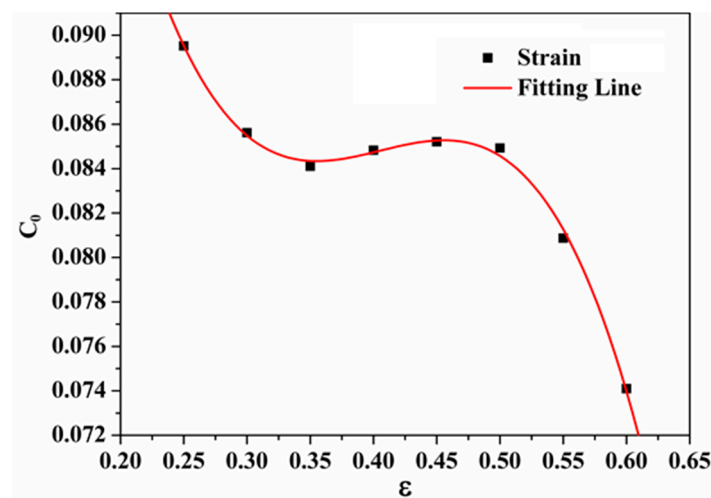


Figure 3. Relationship between $\sigma/(A_1 + B_1\varepsilon + B_2\varepsilon^2)$ and $\ln \dot{\varepsilon}^*$ to determine material parameter C_0 .

Table 1. Parameter C_0 corresponds to the value of the different strains.

ε	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60
C_0	0.08952	0.08562	0.08411	0.08483	0.08521	0.08493	0.08087	0.0741

Fitting the relationship between C_0 and ε , we can find that the C_0 value is a cubic function of strain, $C_0 = C_1 + C_2\varepsilon + C_3\varepsilon^2 + C_4\varepsilon^3$, and the values of parameters C_1 , C_2 , C_3 , and C_4 can be fitted as 0.2017, -0.89301 , 2.23743 , and -1.8398 , respectively, as shown in Figure 4. Huang et al. [45] shows that the dynamic recrystallization degree of 35CrMo steel is different under certain deformation conditions with the increase of strain. It is speculated that the strain dependency of parameter C_0 may be the result of competition between strain hardening and dynamic recrystallization or dynamic recovery during hot deformation.

**Figure 4.** Relationship between C_0 and ε to determine parameters C_1 , C_2 , C_3 , and C_4 .

Similarly, as a function of λ_1 and λ_2 , the strain rate related parameter λ is introduced, and λ is equal to $\lambda_1 + \lambda_2 \ln \dot{\varepsilon}^*$. Then, Equation (2) can be transformed as follows:

$$\frac{\sigma}{(A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C_0 \ln \dot{\varepsilon}^*)} = e^{\lambda(T - T_{\text{ref}})} \quad (5)$$

Taking the natural logarithm on both sides of Equation (5) and one gets:

$$\ln \left[\frac{\sigma}{(A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C_0 \ln \dot{\varepsilon}^*)} \right] = \lambda(T - T_{\text{ref}}) \quad (6)$$

At four deformation temperatures of 1123, 1223, 1323, 1423 K, and three strain rates of 0.1, 1, 10 s^{-1} , the stress values correspond to the above mentioned eight strains. The relationships between $\ln \left\{ \sigma / [(A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C_0 \ln \dot{\varepsilon}^*)] \right\}$ and $(T - T_{\text{ref}})$ can be obtained, as shown in Figure 5. Then, $\lambda_{(\dot{\varepsilon}^*=1)}$, $\lambda_{(\dot{\varepsilon}^*=10)}$, and $\lambda_{(\dot{\varepsilon}^*=100)}$ can be linear fitted as -0.00429 , -0.00339 , and -0.00268 , respectively, when the dimensionless strain rates ($\dot{\varepsilon}^*$) are 1 (Figure 5a), 10 (Figure 5b), and 100 (Figure 5c). Draw $\lambda - \ln \dot{\varepsilon}^*$ curve, and conduct linear fitting, as shown in Figure 6, one gains $\lambda_1 = -0.00426 \text{ K}^{-1}$ and $\lambda_2 = 0.000349607 \text{ K}^{-1}$.

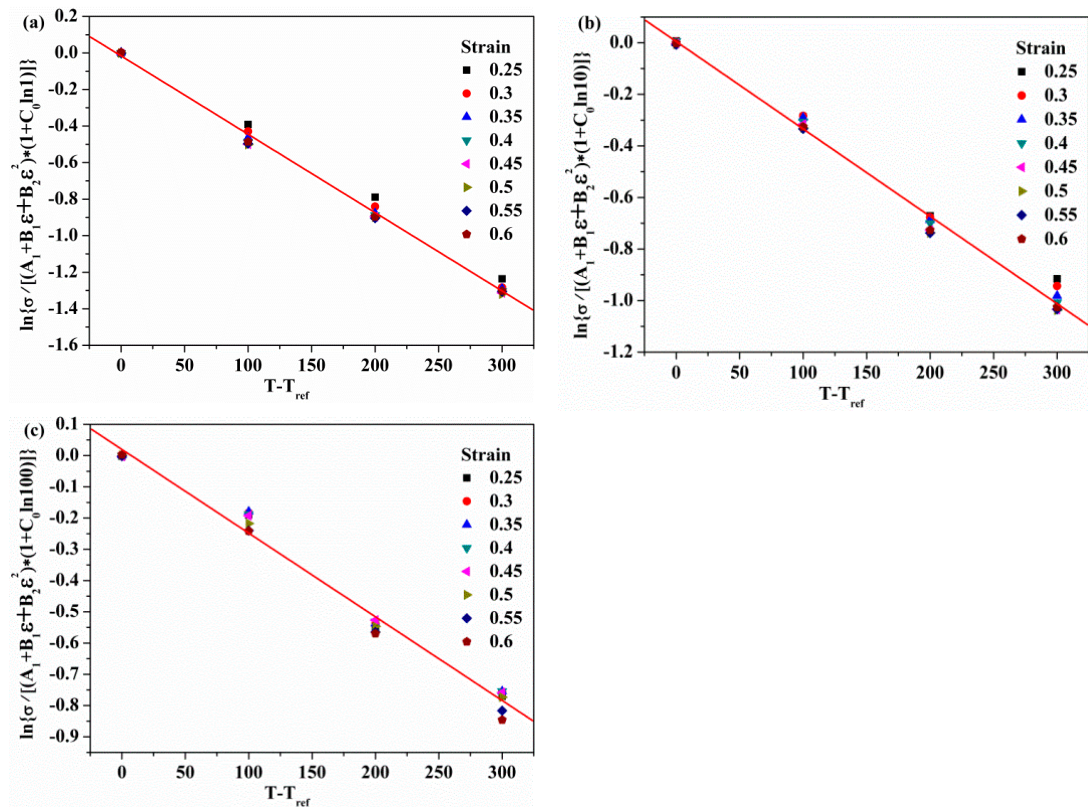


Figure 5. Relationships between $\ln\left\{\sigma / [(A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C_0 \ln \varepsilon^*)]\right\}$ and $(T - T_{ref})$ for different strain rates: (a) $\dot{\varepsilon}^* = 1$; (b) $\dot{\varepsilon}^* = 10$; (c) $\dot{\varepsilon}^* = 100$.

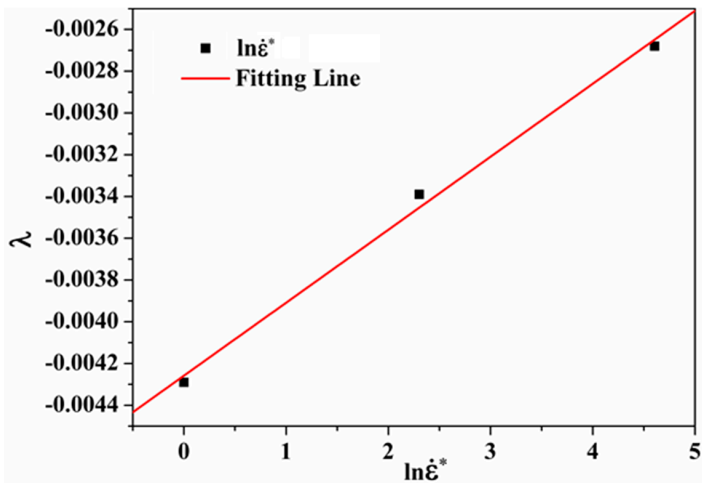


Figure 6. Relationship between λ and $\ln \dot{\varepsilon}^*$ to determine parameters λ_1 and λ_2 .

The results of the modified JC model parameters are shown in Table 2. According to the parameters, calculated the predicted flow stress value, and compared with the experimental results, as shown in Figure 7.

Table 2. Parameters for modified JC (Johnson-Cook) equation for 35CrMo steel.

Parameters	A_1	B_1	B_2	C_1	C_2	C_3	C_4	λ_1	λ_2
Value	114.45	227.75	197.47	0.2017	−0.89301	2.23743	−1.8398	−0.00426	0.000349607

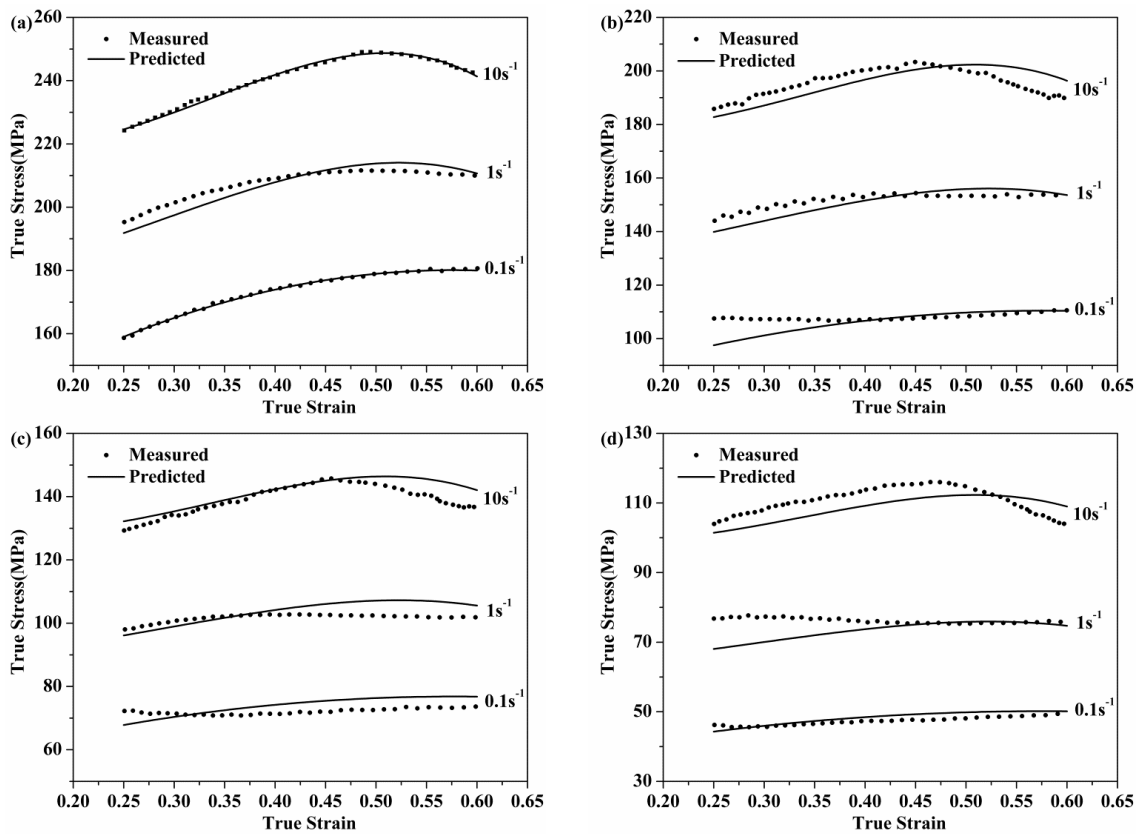


Figure 7. The comparison of the model predictions with experimental results at various temperatures and strain rates: (a) 1123 K; (b) 1223 K; (c) 1323 K and (d) 1423 K.

4.2. Error Analysis of Prediction Results

As shown in Figure 7, it can be observed that the predicted value is in good agreement with the experimental data in most compression conditions. The correlation coefficient (R) is a commonly used statistic can represent the strength of linear relationship between experimental and the predicted values. It should be noted that the higher value of R may not necessarily indicate a better degree of compliance since the model tends to be higher or lower. Therefore, it is necessary to introduce the average absolute error (Δ) to represent the deviation of the predicted values from the experimental date. The mathematical expressions are:

$$R = \frac{\sum_{i=1}^N (\sigma_{\text{exp}}^i - \bar{\sigma}_{\text{exp}}) (\sigma_{\text{p}}^i - \bar{\sigma}_{\text{p}})}{\sqrt{\sum_{i=1}^N (\sigma_{\text{exp}}^i - \bar{\sigma}_{\text{exp}})^2 \sum_{i=1}^N (\sigma_{\text{p}}^i - \bar{\sigma}_{\text{p}})^2}} \quad (7)$$

$$\Delta = \frac{1}{N} \sum_{i=1}^N \left| \frac{\sigma_{\text{exp}}^i - \sigma_{\text{p}}^i}{\sigma_{\text{exp}}^i} \right| \times 100\% \quad (8)$$

where $\bar{\sigma}_{\text{exp}}$ and $\bar{\sigma}_{\text{p}}$ are the mean values of σ_{exp} (Experimental measured flow stress values) and σ_{p} (Model prediction values), respectively, N is the total number of observation points. The R between the experimental and predicted data from modified JC model is 0.99683 (Figure 8), and the Δ for entire ranges is 2.22%. The results show that the modified JC model can accurately and estimate the flow stress of 35CrMo steel and can be used to analyze the problem in forming process.

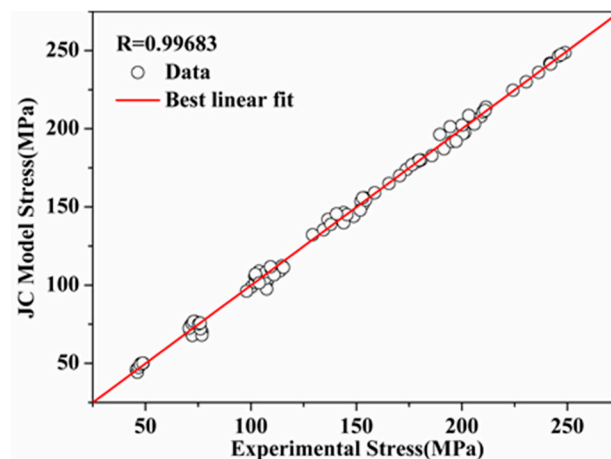


Figure 8. Correlation coefficient between the modified JC model and experiment data over the entire range of strains (0.25–0.6 in steps of 0.05), temperatures (1123–1423 K), and strain rates ($0.1\text{--}10\text{ s}^{-1}$).

5. Conclusions

In this study, a uniaxial compression experimental program is carried out over a wide range of temperatures (1123–1423 K) and strain rates ($0.1\text{--}10\text{ s}^{-1}$) to obtain the flow behavior of 35CrMo steel. The results show that under low temperature and high strain rate, the strain hardening effect is stronger than the dynamic recrystallization softening effect and the true stress-strain curves continues to rise. At high temperature and low strain rate, the stress increased rapidly to the peak after a slight decline, and followed by a steady state flow. This indicates that the strain hardening and recrystallization behavior of 35CrMo steel is affected by temperature, strain, and strain rate, and its true stress-strain curves can be observed typical work hardening and dynamic softening features. Accordingly, a modified JC model was developed, and its prediction results agree well with the experimental results at the selected temperatures and strain rates. The correlation of the predicted value is 0.9968, and the absolute error is about 2.22%.

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

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