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STUDY ON CONSTITUTIVE MODELS OF HOT DEFORMATION FOR 34CrNi3MoV STEEL

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Isothermal constant strain rate compression experiments were conducted on 34CrNi3MoV steel using a thermal simulation experimental machine to study its thermal deformation behavior, with deformation temperatures ranging from 800 - 1 200 °C and strain rates ranging from 0,01 - 10 s^{-1} , and the corresponding stress-strain curves were obtained for 60 % compression. According to the results, through regression analysis of the 1stOpt software, parameter values of three constitutive models were obtained, and then the precision of prediction was compared by different models of flow stress.

Key words: 34CrNi3MoV steel, hot deformation, flow stress, constitutive model

INTRODUCTION

The thermal deformation behavior of metal materials is quite complex, involving work hardening effect and softening effect, and the deformation resistance is affected by coupling factors such as strain rate, strain value and experimental temperature of deformation [1-4]. Based on the fundamental role of constitutive model, many scholars have worked to develop constitutive models with higher fitting accuracy. For example, researchers[4-6] such as Bin Yao, Dong Xu, et al. used the hyperbolic sinusoidal form of coupled polynomials to express the thermal constitutive equation of different materials, which is more accurately calculated but less easy to use in finite element simulations; Zhicheng Cheng et al [7] used a neural network model training function and parameters to obtain a predictive stress model for 42CrMo steel; Zhihui Cai et al [8] studied the Johnson-Cook constitutive model and proposed a modified model of Johnson-Cook equation, which was shown to be a better fit for the quasi-static and dynamic deformation of medium Mn steel. In this study, 34CrNi3MoV steel with the addition of trace alloy is studied , this steel grade is mainly used in the production of military components, so there is less information available to study the thermal constitutive relationship of this steel grade.

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In this paper, the thermal deformation behavior of 34CrNi3MoV steel under different thermal deformation conditions was studied by using a thermal simulation experiment machine, and different high-temperature constitutive equations of 34CrNi3MoV steel were established. The coefficients of the equations were determined by fitting, and the prediction accuracy of different constitutive models was compared. The aim is to provide accurate flow stress model for finite element simulation of metal plastic forming, and to provide necessary theoretical guidance for practical production process.

THERMAL DEFORMATION EXPERIMENT

The experimental steel was taken from a forging stock of 34CrNi3MoV steel from a special steel plant, and the main chemical compositions (mass fraction) were as follows: C 0,31 % - 0,35 %, Ni 3,0 % - 3,3 %, Cr 1,2 % - 1,5 %, Mn 0,5 % - 0,8 %, Mo 0,35 % - 0,45 %, Si 0,15 % - 0,4 %, V 0,1 % - 0,2 %. The samples were processed into φ 8 mm × 12 mm by wire cutting, so that the thermal compression experiments at different thermal deformation conditions could be carried out through hot simulation experiments.

The thermal deformation behavior was tested by thermal compression experiments, and the specific experimental process was as follows: The samples were heated at the rate of 20 °C/s, held for 5 min to complete austenitizing at 1 200 °C, and then cooled at the rate of 10 °C/s to the experimental temperature of 800, 900, 1 000, 1 100, and 1 200 °C, respectively. After holding for 10 s, isothermal-constant strain rate compression was performed at different strain rates (0,01 s^{-1}, 0,1 s^{-1}, 1 s^{-1} and 10 s^{-1}). The maximum of hot compression was 60 %. Displacement-load data were got during the hot compression process. After compression, the samples were immediately water-cooled and quenched.

EXPERIMENTAL RESULTS

According to the test results of the thermal simulation test, the data points were collected and then were transformed into true strain-true stress curve, which is evaluated between 0 and 0,5 of true strain, and the curves of different thermal deformation conditions were shown in Figure 1, and the strain rates during the experiment of (a), (b), (c) and (d) are 0.01 s^{-1}, 0.1 s^{-1}, 1 s^{-1} and 10 s^{-1}, respectively.

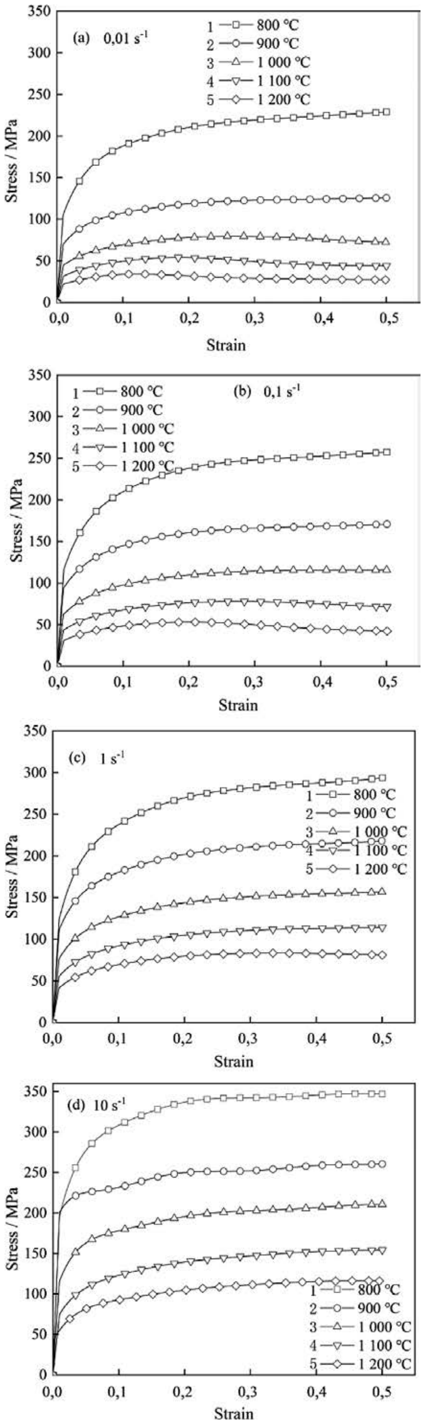

Figure 1 The stress-strain curves under different experimental conditions

(a) 0,01 s^{-1}; (b) 0,1 s^{-1}; (c) 1 s^{-1}; (d) 10 s^{-1}

According to Figure 1, in general: the deformation temperature and strain rate have great influence on the stress. Like most metal materials, the stress decreases when the temperature increases, and the stress increases when the strain rate increases; At the same strain rate, the stress peak moves to the left when increase of deformation temperature; When the deformation temperature is the same, the higher the strain rate is, the higher the stress peak is, and the corresponding strain variable is also larger.

RESULTS AND DISCUSSION

Construction of the constitutive model and determination of parameters

The accurate expression of the constitutive equation contributed significantly to the study of thermal deformation, and different models were proposed by different researchers according to the research objects and experimental approaches. In this paper, three commonly used constitutive relationship models [4-8], namely norton-Hoff Law, Zerili-Armstrong, Generalized Johnson & Cook model, were fitted by 1stOpt software to determine the model parameters.

The Norton-Hoff Law model was shown in Equation (1):

$$\sigma = a_1 \left(a_2 + \varepsilon\right)^{n_1} \left(\dot{\varepsilon}\right)^{n_2} \exp\left(\frac{a_3}{T}\right) \quad (1)$$

where $\dot{\varepsilon}$ denotes the strain rate, s^{-1}; σ denotes the flow stress / MPa; T denotes the thermodynamic temperature / K; ε denotes the strain; a_1, a_2, a_3, n_1 and n_2 are the parameters of Eq. (1).

After transforming in a mathematical way, the parameters of the Norton-Hoff Law model calculated by 1stOpt software were: a_1 = 3,6769, a_2 = -0,008694, a_3 = 4856,0912, n_1 = 0,1237, and n_2 = 0,09685.

The Zerilli-Armstrong model was shown in Equation (2).

$$\sigma = b_1 + b_2 \exp(-b_3 T + b_4 T ln\dot{\varepsilon}) + b_5 \varepsilon^h \quad (2)$$

where b_1, b_2, b_3, b_4, b_5, and h are the parameters of Eq. (2).

The parameters of the Zerilli-Armstrong model calculated by 1stOpt software were: b_1 = 35,9, b_2 = 4528,2642, b_3 = 0,002512, b_4 = 6,6324×10^{-5}, b_5 = -52,2455, and h = -0,2182.

The generalized Johnson & Cook model as shown in equation (3).

$$\sigma = (c_1 + c_2 \varepsilon^{m_1})\left[1 + c_3 \ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})\right](\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})^{m_2}\left(c_4 - c_5 T^{*m_3}\right) \quad (3)$$

where c_1, c_2, c_3, c_4, c_5, m_1, m_2 and m_3 are the parameters of Eq. (3); where $T^* = \frac{T - T_{room}}{T_{melt} - T_{room}}$, T *is the* thermodynamic temperature, K; T_{room} and T_{melt} are the room temperature and the melting temperature of the steel grade, 298,15 K and 1 714,15 K, respectively.

The parameters of the Generalized Johnson & Cook model calculated by 1stOpt software were: c_1 = 0,5989,

c_2 = -26,8689, c_3 = 6,5171 × 10^{-8} , c_4 = 2,4039, c_5 = 3,1369, m_1 = 0,1365, m_2 = 0,09703, and m_3 = -2,0309.

Comparison of the prediction accuracy of three constitutive models

In order to more accurately describe the efficiency of establishing three constitutive relationships, the validity of the above models was verified by introducing the correlation coefficient (*R*) and the average absolute relative error (*AARE*).

$$R = \frac{\sum_{i=1}^{N}\left(E_i-\bar{E}\right)\left(P_i-\bar{P}\right)}{\sqrt{\sum_{i=1}^{N}\left(E_i-\bar{E}\right)^2}\sqrt{\sum_{i=1}^{N}\left(P_i-\bar{P}\right)^2}} \quad (4)$$

$$AARE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{E_i-P_i}{E_i}\right| \quad (5)$$

where and are the test of flow stress values and calculated values, respectively; is the average value of *E*, *P*; is the total numbers of results obtained experimentally.

The magnitude of was usually used to analyze the degree of correlation of linear relationship between the experimental and calculated values, but it did not necessarily represent the degree of agreement, because the predicted data might all be over or under. On the other hand, *AARE* was the average relative error of the calculated value and the experimental value, so it could better represent the consistency between the overall calculated value and the experimental value. In this paper, and were combined to evaluate the accuracy of flow stress prediction.

Table 1 showed the accuracy assessment values under different constitutive models. As could be seen from Table 1 that the *R*-value of both Norton-hoff model and Johnson & Cook model was 0,985; the *R*-value of Norton-Hoff Law model was slightly lower at 0,983. However, compared with 12 % of the Norton-Hoff model and Johnson & Cook model, the *AARE* value of the Norton-Hoff Law model was a little higher, which was 13,2 %.

Figure 2 showed correlation of flow stress data between the experimental and calculated values. For this steel grade, the *R* and *AARE* values were almost the same for the Norton-hoff model and the Johnson & Cook model, but from Figure 2, it can be seen that the Norton-hoff model deviated more at low and medium stress (high temperature, small strain, or low strain rate) compared to the Johnson & Cook model, and the high stress (low temperature, large strain, or high strain rate) were fitted somewhat better.

Table 1 ***R*, R^2 and *AARE* values under different constitutive models**

Parameter	Norton-Hoff Law	Norton-hoff	Johnson & Cook
R	0,983	0,985	0,985
R^2	0,966	0,970	0,970
AARE	13,2 %	11,96 %	12,0 %

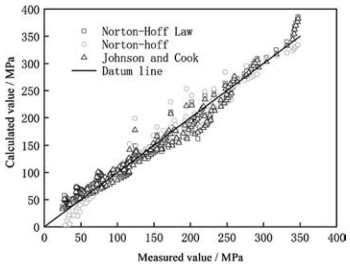

Figure 2 Correlation of data between the calculated and experimental values

CONCLUSION

(1) After transforming in a mathematical way, the constant coefficients of the three commonly used constitutive equations were calculated by 1stOpt software, and the predictive accuracy of the above constitutive equations was verified by the coefficient and *AARE*, and the correlation coefficient of all three constitutive models could reach above 0,98.

(2) The Johnson & Cook model fits better when the 34CrNi3MoV steel is at low to medium stress level, i.e., high temperature, small strain or low strain rate.

(3) The stress results are higher for low temperature, large strain or high strain rate experiments, and the Norton-hoff model is a better fit in these cases.

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Note: Dong Xu is the responsible translator and the corresponding author, Handan, Hebei, China.