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FLOW STRESS BEHAVIOR OF 30CrMoA STEEL UNDER HIGH TEMPERATURE COMPRESSION

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In order to reasonably select the process parameters of the rolling process of 30CrMoA steel, the rheological characteristics of 30CrMoA steel at high temperature were studied. First, the stress-strain curve of 30CrMoA steel in the temperature range of 1 223 K to 1 423 K and the strain rate of 0,01 s^{-1} to 10 s^{-1} was obtained through thermal simulation experiments. Then an empirical constitutive model was established, and the material constants in the established constitutive model were determined by regression analysis of experimental data. Finally, the accuracy of the constitutive model of 30CrMoA steel was verified. The results show that the error between the calculated value and the experimental value is within 5 %, which indicates that the 30CrMoA steel constitutive model has high accuracy.

Key words: 30CrMoA steel, high temperature compression, stress-strain curve, peak stress, constitutive equation

INTRODUCTION

30CrMoA steel has good strength and toughness. It is often used to manufacture train axles, pressure vessels, aircraft structural parts. Using thermal simulation experiments to study the high-temperature rheological properties of 30CrMoA steel, it not only obtain the influence of process parameters such as deformation temperature, deformation rate, and deformation amount on rheological stress, but also provide a theoretical basis for reasonable formulation of metal processing processes at high temperatures [1]. Regarding the research of high temperature rheological properties of alloys, Al-Mg alloys are the most common [2]. The research on 30CrMoA steel is currently focused on heat treatment, surface strengthening and fatigue characteristics. Qinjian Z. et al. [3] proposed the ultrasonic surface strengthening (USS) method, and used this method to experimentally study the basic characteristics of 30CrMoA train axles. Zhang Q. et al. [4] studied the effect of ultrasonic vibration extrusion strengthening (UVET) technology on the surface strengthening of 30CrMoA steel.

In this paper, the stress-strain curve of 30CrMoA steel under high temperature compression is obtained through thermal simulation experiments, and then an empirical flow stress constitutive equation is established. The material constants in the constitutive equation are obtained by linear regression analysis of the stress-strain data obtained from the thermal simulation experiments. Finally, the calculated values of the peak stress are compared with the experimental values to verify the accuracy of the established constitutive equation.

EXPERIMENTAL MATERIALS AND METHODS

The chemical composition (in wt.%) of the 30CrMoA steel used in the experiment is 0,3 C - 0,92 Cr - 0,03 Ni - 0,025 Cu - 0,2 Mo - 0,27 Si - 0,55 Mn - 0,025 S - 0,025 P. The sample size is ϕ 8 × 12 mm. Thermal simulation experiments were performed on a Gleeble - 3500 thermal simulation experiment machine. The experimental data was recorded by the computer. According to the characteristics of the hot rolling process, the temperatures in the experiment were 1 223 K, 1 273 K, 1 323 K, 1 373 K, and 1 423 K, the strain rates were 0,01 s^{-1}, 0,1 s^{-1}, 1 s^{-1}, and 10 s^{-1}, and the maximum deformation was 60 %.

RESULTS AND ANALYSIS OF TRUE STRESS-STRAIN CURVES

Figure 1 is the true stress-strain curve of 30CrMoA steel at different strain rates and different deformation temperatures. It can be seen from Figure 1 that the overall trend of the stress-strain curve is that the flow stress increases rapidly with the increase of the strain at the initial stage, and after reaching the peak stress, the flow stress decreases with the increase of the strain and then stabilizes. At the same strain rate, the higher the temperature, the smaller the flow stress, and the faster the flow stress reaches its peak. At the same temperature, the greater the strain rate, the greater the flow stress, and the greater the strain when the flow stress reaches its peak. When the strain rate is 0,01 s^{-1} and 0,1 s^{-1}, the stress peak is obvious, and the stress-strain curve shows a clear unimodal shape, which indicates that the material undergoes dynamic recrystallization at this strain rate. When the strain rate is 1 s^{-1} and 10 s^{-1}, the stress

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peak is not obvious, the rising rate of the stress-strain curve continues to decrease, and finally stabilizes. The peak stress and steady-state stress are the same, which indicates that the material has undergone dynamic recovery and no dynamic crystallization.

ESTABLISHMENT OF EMPIRICAL CONSTITUTIVE MODEL

The flow stress during hot working of metal depends on the strain rate and deformation temperature. The Arrhenius equation describes the relationship among flow stress, deformation temperature and strain rate is:

$$\dot{\varepsilon} = Af(\sigma)\exp\left[-Q/(RT)\right] \tag{1}$$

Where $\dot{\varepsilon}$ is the strain rate /s^{-1}; A is a material constant, $f(\sigma)$ is a stress function, Q is the deformation activation energy /J·mol^{-1}; R is the gas constant (8,314J·mol^{-1}·K^{-1}), and T is the temperature /K;

The stress function generally has three forms: power function type, exponential function type and hyperbolic sine function type, and their expressions are as follows:

$$f(\sigma) = \begin{cases} \sigma^{n_0} & \alpha\sigma < 0{,}8 \\ \exp(\beta\sigma) & \alpha\sigma > 1{,}2 \\ [\sinh(\alpha\sigma)]^n & \forall\sigma \end{cases} \tag{2}$$

Where n_0, β, α and n are the material constants to be solved, $\alpha = \beta/n_0$.

The stress function in the form of power function is mainly suitable for low stress conditions, the stress function in the form of exponential function is mainly suitable for high stress conditions, and the stress function in the form of a hyperbolic sine function proposed by Sellars et al. is applicable for all stress conditions [5]. This paper uniformly uses the peak stress σ_p to describe the constitutive relationship. The statistics of the peak stress σ_p at different temperatures and strain rates are as Table 1.

Table 1 **Peak stress σ_p /MPa at different temperatures and strain rates**

Strain rate $\dot{\varepsilon}$ / s^{-1}	Deformation temperature T / K				
	1 223	1 273	1 323	1 373	1 423
0,01	71,4	57,8	47,7	36,7	31,2
0,1	107,4	89,0	73,5	60,0	50,0
1	154,0	130,9	109,2	92,3	77,6
10	214,8	168,7	150,5	131,5	104,0

In the hot working process of metal, the stress function in the form of hyperbolic sine function is often used to express the plastic strain rate:

$$\dot{\varepsilon} = A\left[\sinh\left(\alpha\sigma_p\right)\right]^n\exp\left[-Q/(RT)\right] \tag{3}$$

Under low stress conditions:

$$\dot{\varepsilon} = A_1\sigma_p^{\,n_0}\exp\left[-Q/(RT)\right] \tag{4}$$

Under high stress conditions:

$$\dot{\varepsilon} = A_2\exp(\beta\sigma_p)\exp\left[-Q/(RT)\right] \tag{5}$$

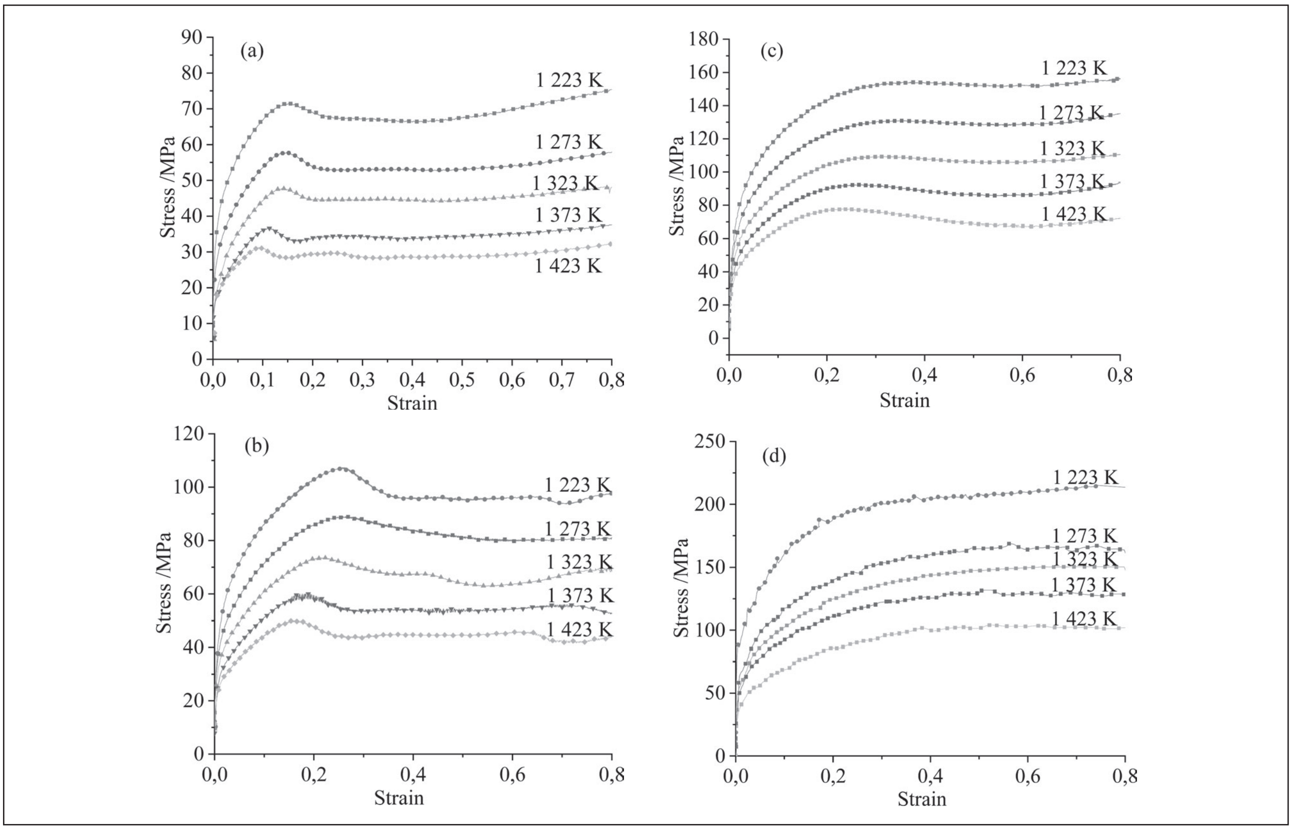

Figure 1 True stress-strain curve of 30CrMoA steel
(a) $\dot{\varepsilon}$ = 0,01s^{-1}; (b) $\dot{\varepsilon}$ = 0,1s^{-1}; (c) $\dot{\varepsilon}$ = 1s^{-1}; (d) $\dot{\varepsilon}$ = 10s^{-1}

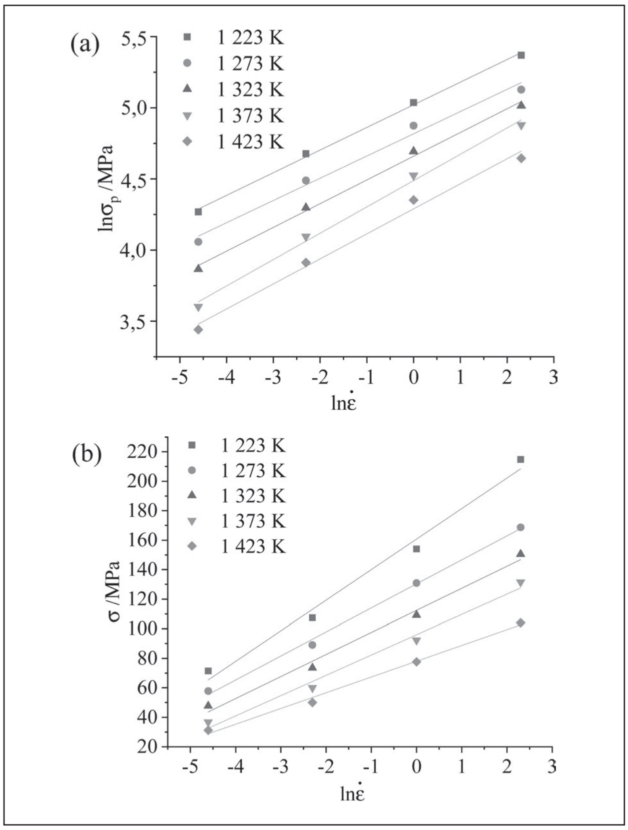

Figure 2 Relationship between strain rate and peak stress at different temperatures (a) $\ln\dot{\varepsilon} - \ln\sigma_p$; (b) $\ln\dot{\varepsilon} - \sigma_p$

Performing a logarithmic operation on both sides of equation (8) and (9):

$$\ln \dot{\varepsilon} = n_0 \ln \sigma_p + \ln A_1 - Q/(RT) \tag{6}$$

$$\ln \dot{\varepsilon} = \beta \sigma_p + \ln A_2 - Q/(RT) \tag{7}$$

The relationship between ln$\dot{\varepsilon}$ and lnσ_p can be obtained from Table 1, and curves between ln$\dot{\varepsilon}$ and σ_p are shown in Figure 2. Obviously, the relationship curve between them is a straight line. From equations (6) and (7), It can be concluded that the inverse of the slope of straight line is n_0 and β, and the average value n_0 is 5,929 and β is 0,066MPa^{-1}. Then $\alpha = \beta/n_0 = 0{,}011$ MPa^{-1}.

Performing a logarithmic operation on both sides of equation (3):

$$\ln \dot{\varepsilon} = n \ln[\sinh(\alpha\sigma_p)] + \ln A - Q/(RT) \tag{8}$$

Substituting α = 0,011 MPa^{-1} into equation (8) can obtain the relationship curve between ln$\dot{\varepsilon}$ and ln[sinh($\alpha\sigma_p$)], as shown in Figure 3. From equation (8), it can be seen that the inverse of the slope of straight line in Figure 3 is n, and its average value n is 4,403.

When the strain rate $\dot{\varepsilon}$ is a constant value, the partial differential equation for 1/T in Equation (9) is:

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

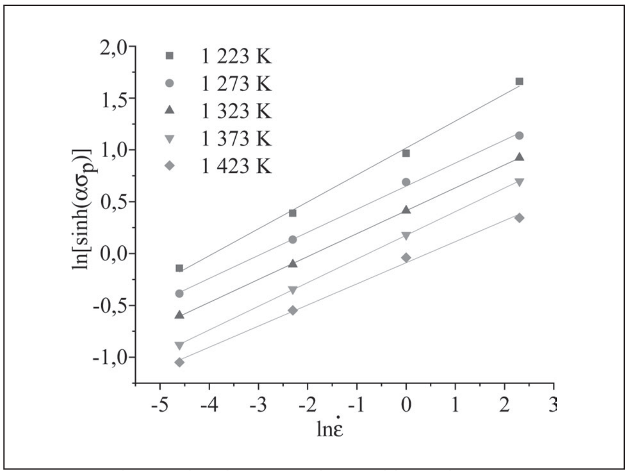

Figure 3 Relationship between ln$\dot{\varepsilon}$ and ln[sinh($\alpha\sigma_p$)] at different temperatures

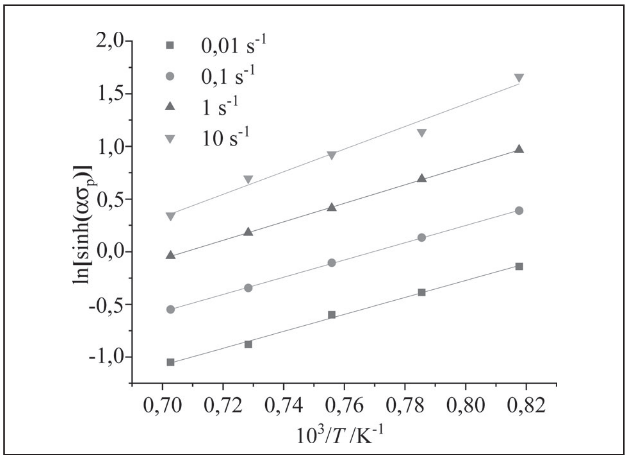

Figure 4 Relationship between 1/T and ln[sinh($\alpha\sigma_p$)]

The relationship curve between 1/T and ln[sinh($\alpha\sigma_p$)] are shown in Figure 4. From equation (9) that the slope of straight line in Figure 4 is Q/nR. substituting the values of n and R into the slope calculation formula can obtain the average deformation activation energy Q = 261,85kJ·mol^{-1}.

It can be known from the equation (8) that the intercept of straight line in Figure 3 is $Q/(nRT)$-(ln$A$)/n, and substituting Q, n, R and T for A= 3,67 × 109s^{-1}. Substituting the material constants A, α, Q and n into equation (3) to obtain an empirical constitutive equation for 30CrMoA steel:

$$\dot{\varepsilon} = 3{,}67\times 10^{9}\left[\sinh(0{,}011\sigma_p)\right]^{4{,}403}\exp[-261850/(RT)]$$

COMPARISON OF CALCULATED AND EXPERIMENTAL VALUES OF PEAK STRESS

In order to verify the accuracy of the constitutive model of the 30CrMoA steel, the calculated value of the stress peak was compared with the experimental value. The results are shown in Table 2.

It can be known from Table 2 that the calculated value of the stress peak is very close to the experimental value, and the maximum error is 4,4 %. Therefore, the 30CrMoA steel constitutive model established in this paper has high accuracy and can provide a theoretical basis for the formulation of 30CrMoA steel hot forming processing technology.

Table 2 **Comparison of calculated and experimental values of peak stress**

Strain rate $\dot{\varepsilon}$ / s^{-1}	Deformation temperature: 1 273 K		
	Experimental value / MPa	Calculated value / MPa	Error / %
0,01	57,83	55,67	3,7
0,1	89,04	86,32	3,0
1	130,92	125,11	4,4
10	168,74	168,90	0,1
Strain rate $\dot{\varepsilon}$ / s^{-1}	Deformation temperature: 1 323 K		
	Experimental value / MPa	Calculated value / MPa	Error / %
0,01	47,72	45,91	3,8
0,1	73,53	72,76	1,0
1	109,24	108,56	0,6
10	150,47	150,72	0,2
Strain rate $\dot{\varepsilon}$ / s^{-1}	Deformation temperature: 1 373 K		
	Experimental value / MPa	Calculated value / MPa	Error / %
0,01	36,68	38,19	4,1
0,1	60,01	61,53	2,5
1	92,25	94,16	2,1
10	131,53	134,32	2,1

CONCLUSIONS

The flow stress constitutive equation of 30CrMoA steel is:

$$\dot{\varepsilon} = 3{,}67\times10^{9}\left[\sinh\left(0{,}011\sigma_p\right)\right]^{4{,}403}\exp\left[-261850/(RT)\right]$$

The error of the peak stress between the calculated value and the experimental value is within 5 %, and the established constitutive equation has high accuracy.

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Note: The responsible translator for English language is S. Zhang, Ningbo, China