A Study on High Temperature and High Strain Rate Dynamic Constitutive Relation of Q345 Steel

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Abstract — In order to accurately describe the dynamic mechanical behavior of Q345 steel at both room temperature and high temperature, we carried our the Gleeble test and Split Hopkinson Press Bar (SHPB) test of Q345 steel. We obtained the mechanical properties and stress-strain curves of the material under different conditions, and analyzed the influence of the temperature and the strain rate on the flow stress of the material. The constitutive model of Q345 steel at high temperature and high strain rate was established by using the least square method. The constitutive model of Q345 was used in the simulation model. The simulation result and experiment result both verified the correctness of the constitutive model of Q345 steel.

Keywords-high strain rate; Q345; Gleeble; constitutive model; least square method

I. INTRODUCTION

Along with the progress of human society and the development of science and technology, the application fields and the application conditions of the materials continue to expand, which are especially the high temperature, high pressure and high velocity deformation and other extreme conditions [1,2]. The influence of the temperature and strenuous exercise of the lattice will produce deformation delay for the material and the strain rate sensitivity [3,4] at high temperature and high velocity deformation, which will change the constitutive model of the material [5,6,7,8]. Affected in turn by the inertia and the violent transfer of the material in the high speed deformation, the deformation ability of the material will promote, which produces quasi stable deformation, and the dynamic effects such as the instability, the necking don't appear [9].

As a kind of low alloy steel, Q345 steel has the largest production in the world, which is widely used in architectural construction, automotive energy, national defense, military and aerospace and other fields. Previous studies of Q345 steel mainly concentrate in normal mechanical behavior and constitutive model at room temperature and low strain rate. The model is not sufficient to describe the dynamic behavior of the material under high temperature and high strain rate [10,11]. Therefore, it has practical significance and scientific value to study the constitutive relation of Q345 steel under high temperature and high strain rate.

Johnson-Cook equation, which is a constitutive equation based on dislocation dynamics, can be used to describe metal rheological behavior under large deformation, high strain rate and high temperature [12,13,14,15,16,17]. In this paper, the dynamic performance of Q345 steel under high temperature and high strain rate was studied based on Johnson-Cook equation by thermal simulation experiment and dynamic impact experiments [18,19]. The influence of temperature and strain rate on the constitutive relation of Q345 steel was obtained under different conditions, and the constitutive equations of Q345 steel under high temperature and high strain rate conditions were established.

II. MECHANICAL PROPERTIES EXPERIMENT

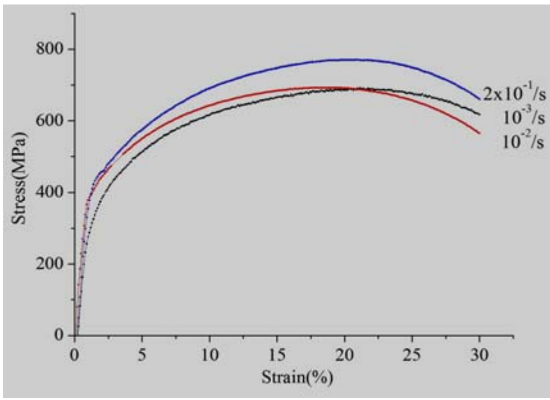
A. Gleeble tensile experiment at room temperature

The experimental material is Q345 steel, and its chemical composition is shown in Table 1.

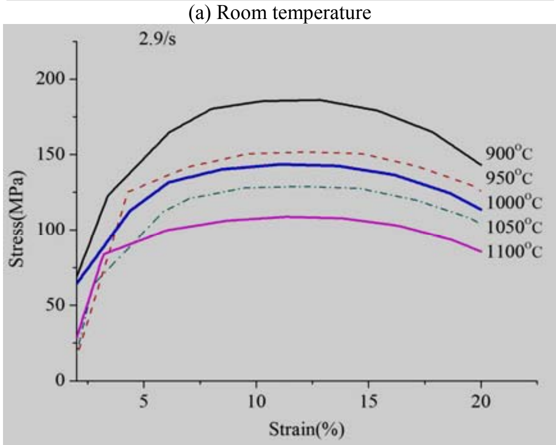
TABLE 1 CHEMICAL COMPOSITION OF Q345 (WT%)

C	Mn	Si	S	P
0.16	1.59	0.43	0.004	0.013

At 25°C, Gleeble tensile experiments were completed three times under three strain rate conditions which were respectively $\dot{\varepsilon}_1$ =10^{-3}/s, $\dot{\varepsilon}_2$ =10^{-2}/s, $\dot{\varepsilon}_3$ =2×10^{-1}/s. The stress strain curve obtained from experimental results is shown in Fig. 1(a). The yield strength under $\dot{\varepsilon}_1$ =10^{-3}/s is significantly less than that of $\dot{\varepsilon}_3$ =2×10^{-1}/s. Test result shows that the strain rate sensitivity effect and strain hardening effect are obvious with the increase of strain rate.



(a) Room temperature



(b) High temperature

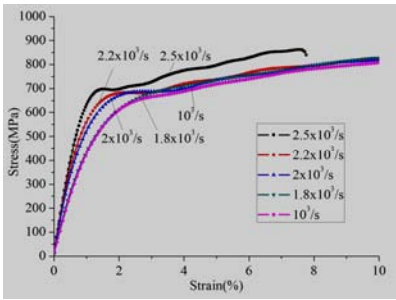
Figure 1.Gleeble tensile curves.

B. Gleeble tensile experiment at high temperatures

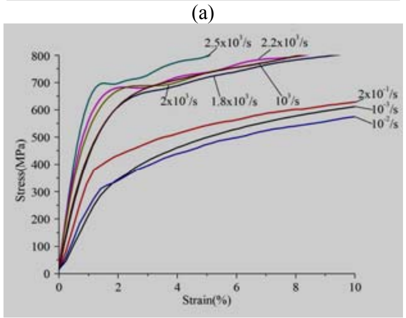
In three strain rate condition of $\dot{\varepsilon}_1$ =2.9/s, $\dot{\varepsilon}_2$ =29/s, $\dot{\varepsilon}_3$ =58/s, and different temperature condition of 900°C, 950°C,1000°C, 1050°C and 1100°C, Gleeble tensile experiments were completed. The stress and strain curves obtained from experimental results are shown in Fig. 1 (b). The yield strength and tensile strength of the material decrease gradually with the increase of experimental temperature, which shows a significant effect of temperature softening.

C. Hopkinson pressure bar experiment

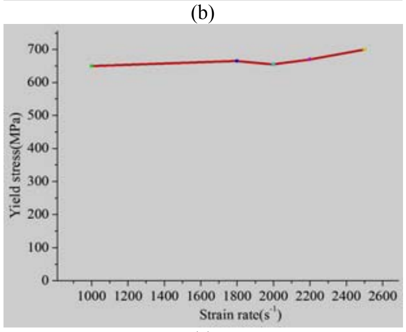
In order to obtain the dynamic mechanical property of the material under high strain rate, SHPB experiments were implemented at room temperature and under five strain rates which were respectively $\dot{\varepsilon}_1$ =10^3/s, $\dot{\varepsilon}_2$ =1.8×10^3/s, $\dot{\varepsilon}_3$ =2×10^3/s, $\dot{\varepsilon}_4$ =2.2×10^3/s, $\dot{\varepsilon}_5$ =2.5×10^3/s. The experimental results are shown in Fig. 2 (a) and (b), most of the curves have obvious yield platforms. When the strain rate is high, the material will smaller deform then enter the yield stage. With the increase of the strain rate, the material performance shows obvious strain rate effect.



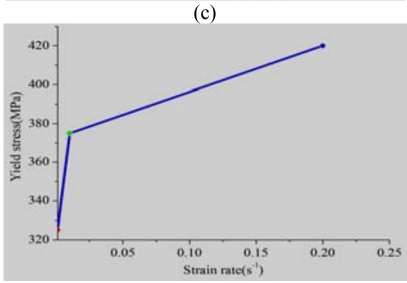
(a)



(b)



(c)



(d)

Figure 2. Experimental results of Hopkinson

Compared with the tensile experiments under the condition of different strain rate and of room temperature, the yield strength change curve of the material at high strain rate are shown in Fig. 2 (c). The curve is smooth, and the maximum growth rate is 7.69%. Fig. 2 (d) shows that the yield strength has a significant upward trend under the low strain rate (10^{-3}/s-2×10^{-1}/s), and the maximum growth rate is 30.43%. The experiment results show that the sensitivity of material strain rate at range of 10^3/s-2.5×10^3/s is lower than that of the low strain rate range.

III. CONSTITUTIVE RELATION ESTABLISHMENT

A. Constitutive relation model determination

An ideal constitutive model for materials at high strain rate should consider the relationship between strain rate and temperature. The model can accurately describe the strain and strain rate with the variation of load. The number of parameters in the model should reduce as possible, and the equation should have good convergence.

Johnson-Cook constitutive relation expression is:

$$\sigma=\left[A+B\varepsilon^{n}\right]\left[1+C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1-\left(T^{*}\right)^{m}\right] \quad (1)$$

In the formula: σ is flow stress; $\dot{\varepsilon}$ is strain rate; $\dot{\varepsilon}_0$ is reference strain rate; *A* is yield strength under $\dot{\varepsilon}_0$ and reference temperature; C is strain rate sensitivity coefficient; *m* is temperature effect coefficient; *B* and n are strain hardening parameter.

B. Johnson—Cook constitutive model parameters determination

Two assumptions are applied to the constitutive relation of Johnson-Cook [20]: 1) The constitutive relation under different stress state can be used to describe the relationship between the effective stress, effective strain and effective strain rate. The form of the equation is the same under three stress states of tension condition, that is the equation in the stress condition of tension, compression and torsion is the same and is processed by the average; 2) The variation of effective strain, effective strain rate and temperature is considered to be equivalent effect on the effective stress, and can be used as separated variables. This illustrates that segregation variable method can be used to determine some parameters.

So the Johnson-Cook constitutive relationship could be divided into three effects. The three effects of Formula (1) from left to right are respectively strain hardening effect, strain rate sensitivity effect and temperature softening effect. The parameters of formula (1) are obtained by using the three effects.

(1) Determination of parameters *A*, *B* and *n*

B and n are the strain hardening coefficients, which correspond to the strain hardening effect. The first bracket in the formula (1) corresponds to the stress-strain relationship of $T=T_r$, $\dot{\varepsilon}=\dot{\varepsilon}_0$. So the values of *B*, n and *A* can be determined by the stress-strain curves measured at room temperature, which were solved by Gleeble tensile test data. The formula (1) was converted to:

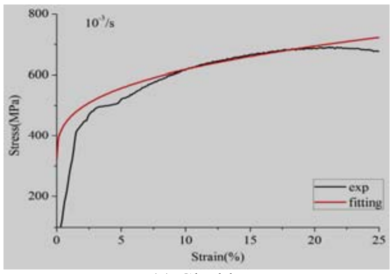
$$\sigma=A+B\varepsilon^{n} \quad (2)$$

A is the yield strength when ε =0.

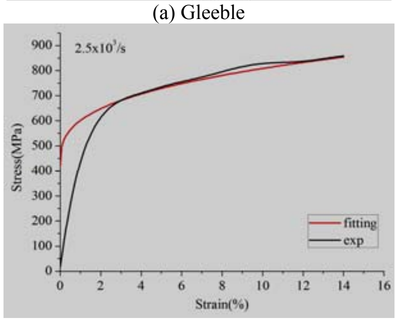
Transposes, and take natural logarithm:

$$\ln(\sigma-A)=\ln B+n\ln\varepsilon \quad (3)$$

Set $\ln(\sigma-A)$ =*y*, $\ln B$ =*a*, n=*b*, $\ln\varepsilon$ =*x*, and converts formula (3) to the form of $y=a+bx$. Solved *a* and *b* by using the least square method. Then the values of *B* and *N* were obtained, and get *A*=320MPa, *B*=633.01MPa, *n*=0.33. As Fig. 3 (a) shows, the fitting curves of strain hardening effect agrees well with the experimental curves.



(a) Gleeble



(b) SHPB

Figure 3. Fitting at room temperature.

(2) Determination of parameter *C*

The parameter *C* corresponds to the strain rate sensitivity effect, which is obtained from the SHPB experiment data.

The flow stress of ε =0 was obtained by the formula (2) :

$$\sigma=A(1+C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}) \quad (4)$$

Take $\dot{\varepsilon}_0$ =10-3/s, and above formula can be converted to:

$$\frac{\sigma}{A}-1=C\ln\frac{\dot{\varepsilon}}{10^{-3}} \quad (5)$$

Set *C*=*a*, $\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}=x$, $\frac{\sigma}{A}-1=y$, and converted formula(5) to the form of $y=ax$. *a* is solved by using the least square method, and get C=0.021. Fig. 3 (b) shows the strain hardening effect agrees well with the experimental results.

(3) Determination of parameter m

M is the temperature softening effect parameter, which was solved by using Gleeble high temperature tensile datas.

Set: $D=(A+B\varepsilon^{n})[1+C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}]$ (6)

The formula (1) is converted to:

$$\sigma = D(1 - T^{*m}) \tag{7}$$

Set $\ln(1-\frac{\sigma}{D}) = y$, m=a, $\ln T^{*} = x$, and converted formula (7) to the form of *y=ax*. Solved m by using the least square method, and the result is *m*=0.475.

As Table 2 shows, the fitting results of strain hardening effect are compared with the experimental results. The difference between the fitting curve and the experimental curve are large, so the coefficients need to modify.

TABLE 2 DIFFERENCE

Strain rate /s^{-1}	Difference /%
2.9	13.45
29	14.28
58	33.33

C. *Coefficient correction*

In order to obtain the most accurate fitting results, the parameter *F* is introduced, thus the temperature soften term ($1-T^{*m}$) convert to ($1-FT^{*m}$).Then formula (7) is converted to:

$$\sigma = D(1 - FT^{*m}) \tag{8}$$

Set *F*=0.95, *m*=0.471. Then the flow stress equation is:

$$\sigma = (320 + 636.01\varepsilon^{0.33})(1 + 0.021\ln\frac{\dot{\varepsilon}}{10^{-3}})(1 - 0.95F^{0.471}) \tag{9}$$

In this paper, experimental data of the reference strain rate ($\dot{\varepsilon}_0$ =10^{-3}/s) is used to fit the Johnson-Cook equation. The equation requires the experimental data with a strain rate of 1/s as a reference; however the strain rate of 1/s was not tested. The model parameters which fit the strain rate of $\dot{\varepsilon}_0$ =10^{-3}/s are modified as the model parameters of 1/s.

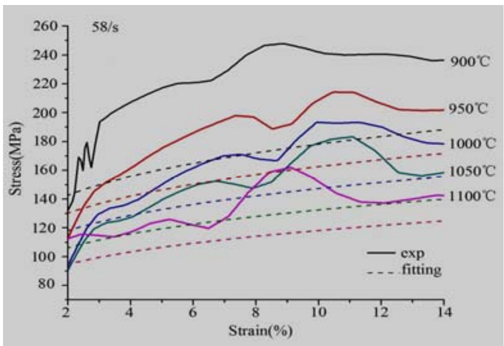
Therefore:

$$\sigma = (320 + 636.01\varepsilon^{0.33})(1 + 0.021\ln\frac{1}{10^{-3}}) = (\sigma_1 + \sigma_1'\varepsilon^{0.33})(1 + C\ln 1) \tag{10}$$

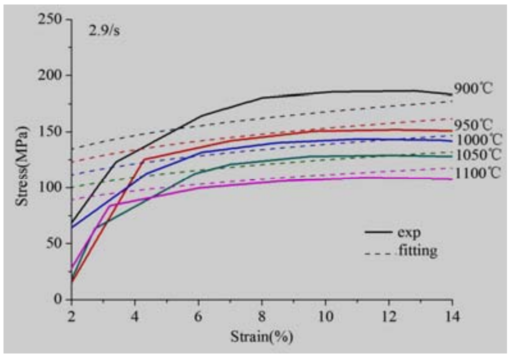
The modified parameters are: *A*=366.42, *B*=728.27, *n*=0.33, *C*=0.021, *F*=0.95, *m*=0.471.

Johnson—Cook flow stress equation is:

$$\sigma = (366.42 + 728.27\varepsilon^{0.33})(1 + 0.021\ln\dot{\varepsilon})(1 - 0.95T^{*0.471}) \tag{11}$$



(a) $\dot{\varepsilon}$ =2.9/s



(b) $\dot{\varepsilon}$ =58/s

Figure 4. Comparison of fitting results

The fitting results are shown in Fig. 4. The modified equation is not very accurate to describe the rheological behavior of high temperature section. The error between the predicted value and the experimental value increases with the increment of strain rate range, which may be related to hypothesis of the equation.

The equation can be divided into three parts which are strain hardening effect, strain rate effect, temperature effect. In this paper, it can be assumed that the three effects are independent each other. The effect of temperature is not considered when fitting coefficient *C,* so the formula (11) is only applicable for the condition of room temperature.

In order to establish the constitutive equation which is applicable to high temperature in this paper, a correction coefficient is added under the condition of formula (11). This correction coefficient is only suitable for the condition of high temperature. The formula (11) is converted to:

$$\sigma = (366.42 + 728.27\varepsilon^{0.33})(1 + 0.021\ln\dot{\varepsilon})(\dot{\varepsilon})^{\alpha}(1\text{-}0.95T^{*m}) \tag{12}$$

The value of *α* is obtained by using Gleeble high temperature experimental data, and get *α*=0.041. The maximum errors between the results of the modified equation and the experiment are shown in table 3.

TABLE 3 CORRECTION RESULTS

Strain rate /s^{-1}	Before correction /%	After correction /%
2.9	7.67	7.62
29	24.76	9.89
58	32.51	12.03

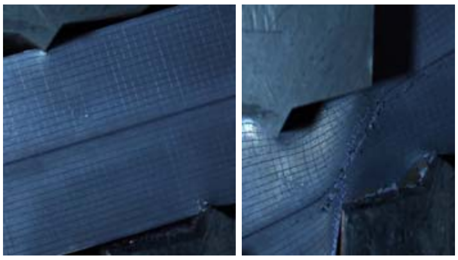
The results show that the modified equation and the fitting of the experimental data are obviously better than before, and the difference of the modified equation remarkably reduces. It shows that the modified equation is more suitable to describe the high temperature rheology of Q345 steel. Constitutive equation of Q345 is:

$$\sigma = (366.42 + 728.27\varepsilon^{0.33})(1 + 0.021\ln\dot{\varepsilon})(\dot{\varepsilon})^{\alpha}(1\text{-}0.95T^{*m}) \tag{13}$$

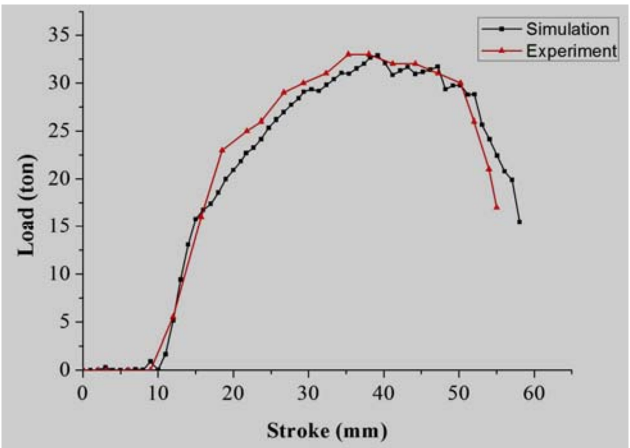
In the formula: $a = \begin{cases} 0\ (room\ temperature) \\ 0.041\ (high\ temperature) \end{cases}$

D. *Experimental verification*

The modified constitutive equation was introduced into FEM simulation software to simulate the dynamic behavior (high temperature and high speed shear), and its results were compared with the experimental results. As Fig. 5 shows, the simulation results of constitutive model agree well with the experimental results, which indicates that the Q345 constitutive equation established in this paper can reflect the dynamic mechanical behavior of the material at high temperature and high strain rate.



(a) Before shear (b) Shear process



(c) Load stroke curve

Figure 5. High temperature, high speed shear on thick plates.

IV. CONCLUSIONS

(1) Q345 steel has obvious strain rate sensitivity effect. In different strain rate ranges, the strain rate sensitivities are different. The experimental results show that the strain rate sensitivity effect of the material in the strain rate range of 10^3/s-2.5×10^3/s is much stronger than that in the strain rate range of 10^{-3}-2×10^{-1}/s. Therefore, the change of the strain rate is not obvious in the specific area of the material.

(2) The yield strength of the material decreases gradually at 900℃-1100℃, which indicates that the Q345 steel has obvious temperature softening effect at high temperature.

(3) Based on the mechanics experiment, the experimental data were fitted by the least square method, and the flow stress equation parameters of the Johnson-Cook model were obtained. The error of the equation was analyzed, and the temperature term of the parameter was modified. The constitutive relation was established, as follows:

Johnson—Cook flow stress equation:

$$\sigma = (366.42 + 728.27\varepsilon^{0.33})(1 + 0.021\ln\dot{\varepsilon})(\dot{\varepsilon})^{\alpha}(1\text{-}0.95T^{*m}) \quad (13)$$

In the formula: $a = \begin{cases} 0\ (room\ temperature) \\ 0.041\ (high\ temperature) \end{cases}$

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