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JOHNSON-COOK (JC) CONSTITUTIVE EQUATION FOR ZGMn18 HIGH MANGANESE STEEL

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In the Finite element simulation, the constitutive equation of the material has an important influence on the simulation results. In order to obtain the constitutive model of ZGMn18 high manganese steel, the constitutive model of ZGMn18 high manganese steel under the condition of quasi-static strain rate at room temperature ($10^{-1}s^{-1}$, $10^{-2}s^{-1}$, $10^{-3}s^{-1}$) compression experiment was conducted to obtain the compression experimental data of ZGMn18 high manganese steel at different rates. According to the experimental results, the parameters of Johnson-Cook constitutive equation of ZGMn18 high manganese steel are deduced, and the Johnson-Cook constitutive model of ZGMn18 high manganese steel at room temperature is obtained. Finally, the prediction results of the model are compared with the experimental data, and the prediction curves are in good agreement, which verifies the feasibility of the model.

Keywords: ZGMn18, compressive test, constitutive model, stress-strain curves, compresive test

INTRODUCTION

High manganese steel (ZGMn18) is traditionally used as a ductile anti-wear material under high stress and high impact conditions. With the development of modern industry, large equipment continues to appear in metallurgy, mining and other industries, such as mining, crushing, mining equipment, its anti-wear accessories weigh several tons to more than ten tons, and the effective thickness is more than 100mm. The traditional high manganese steel is difficult to meet the actual needs no matter from the production technical requirements or use performance requirements. Ultra-high manganese steel has excellent wear resistance, high toughness and strong water toughening ability. The work hardening degree of the impact plate is greater than that of ZGMn13, the highest hardness is close to HV 800, and the service life of the impact plate is increased by more than 50 %. There are many applications of ultra-high manganese steel.

The constitutive equation of materials is the law that must be followed in the deformation process of materials and describes the mechanical behavior of materials under load. One of the central tasks in the study of mechanical properties of materials is to establish constitutive models which can describe the mechanical response of materials under various loading conditions. The constitutive relation of materials is the link between deformation and response of materials, which plays an irreplaceable role in the research and development of plastic forming theory and technology. It includes yield criterion, hardening law and stress-strain relationship, among which stress-strain relationship reflects the characteristics of specific materials, and it is particularly important for the strength design and calculation application of materials.

The constitutive relation of metal materials under impact load is usually described by viscoplastic model [1]. The so-called ideal viscosity refers to the fluid which conforms to the flow law of Newton fluid. The stress and shear rate have a linear relationship. When the external force is applied, the strain develops linearly with time. The so-called ideal plasticity means that the material does not have the hardening stage, that is, the stress-strain curve is replaced by a horizontal line after the stress exceeds the yield point. In practice, plasticity and hardening are inseparable.

According to the types of hardening, it can be divided into isotropic hardening, follow-up hardening and mixed hardening [2]. Viscoplastic model is a combination of solid plasticity and fluid viscosity model. Current thermoviscoplastic constitutive models can be divided into two categories [3] : (1) empirical constitutive models, such as Johnson-Cook(JC) model; (2) semi-empirical and semi-theoretical constitutive models, such as Zerilli and Annstrong(ZA) model [4], Mechanical Thresh Stress(MTS) model [5], Steinberg(SG)[6], etc., based on dislocation dynamics theory.

Johnson-Cook constitutive model of ZGMn18 high manganese steel was fitted according to the stress-strain curves of ZgMn18 high manganese steel under different quasi-static strain rates ($10^{-1}s^{-1}$,$10^{-2}s^{-1}$,$10^{-3}s^{-1}$) at room temperature, and the relevant constitutive parameters of

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the material were obtained. The predicted results of the model were compared with the experimental data, and the predicted curves were in good agreement.

EXPERIMENT DESIGN

High manganese steel is widely used in high stress and high impact conditions because of its excellent wear resistance, high toughness and strong water toughening ability. Its main components are shown in Table 1:

Table 1 **Chemical composition of ZGMn18 / wt.%**

C	Mn	Cr	Si	S	Al	Ti	V	P
1,1-1,6	16-22	1,5-4	0,3-1	<0,05	<0,2	<0,2	<0,5	<0,1

The sample material is ZGMn18 high-manganese steel, machined into a cuboid of 11,30 mm × 11,16 mm × 24,47 mm and a cylinder of ∅ 4 mm × 4 mm, and made a compression test on it. The quasi-static compressive stress-strain curves of ZGMn18 high manganese steel at different strain rates are shown in Figure 1.

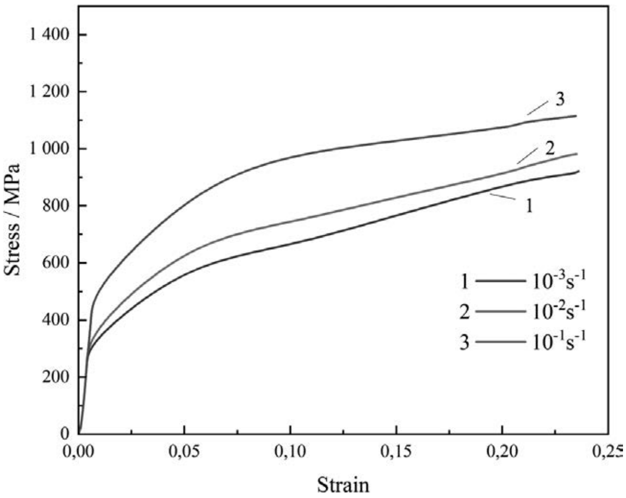

Figure 1 Stress-strain curves of ZGMn18 high manganese steel at different strain rates at room temperature

INTRODUCTION TO JOHNSON-COOK CONSTITUTIVE MODEL

Johnson-Cook constitutive model is composed of three components, the first component characterizes the strain hardening effect, the second characterizes the strain rate hardening effect, and the third characterizes the temperature softening effect, and the three components are combined to form the constitutive relationship of the material. The specific form of its equation is as follows:

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

Where, A, B, n, C and m are material parameters; $\dot{\varepsilon}^{*}$ is dimensionless plastic strain rate, $\dot{\varepsilon}^{*} = \dot{\varepsilon} / \dot{\varepsilon}_0$; ε is the equivalent plastic strain, $\dot{\varepsilon}_0$ is the reference plastic strain rate, this article takes $\dot{\varepsilon}_0 = 10^{-3}s^{-1}$; $T^{*} = \left(T - T_r\right)/\left(T_m - T\right)$, T is the ambient temperature of the sample, T_r is the reference temperature, T_m is the melting point temperature.

In JC model, the equivalent stress is composed of three products. The model is simple and easy to use, so it is widely used. It is the most successful constitutive model to reflect the dynamic mechanical behavior of metal materials at present. A variety of important material parameters have been obtained, and almost all relevant commercial programs (ABAQUS, Ansys, etc.) have material modules with JC constitutive equation options. It should be said that, from the details, JC constitutive equation can not fully reflect some characteristics of materials. Therefore, it is necessary to select other models or modify the JC constitutive equation in the case of particularly strict requirements on materials.

Because the JC model has the characteristics of clear physical meaning and simple form, the JC model is used in this paper to fit the constitutive equation of high manganese steel. However, because JC constitutive model can not fully reflect some characteristics of materials in detail, it is revised. The revision of JC model is reflected in three aspects:

(1) **Temperature effect**. In this paper, since the experiment is conducted at room temperature, that is, when $T = T_r$, $T^{*} = 0$.

(2) **Parameter *B***. In the JC model, parameter B is a parameter of the material; In this paper, B is fitted as a function of strain in order to better reflect the mechanical properties of materials.

(3) **Parameter *C***. In the JC model, parameter C is a parameter of the material; Similarly, in this paper, C is fitted as a function of strain in order to better reflect the mechanical properties of materials.

JOHNSON-COOK CONSTITUTIVE MODEL WAS ESTABLISHED

In scientific research, improper design and processing of research design, index measurement, data analysis and result inference may lead to a variety of errors, among which the most important one is the error between experimental data and simulation results. The reasons may be as follows:

(1) **Measurement error**. When measuring the workpiece in the process of working procedure adjustment and processing, due to the influence of measuring method, measuring tool accuracy and other factors on the accuracy of the measurement results, such as explosive thickness measurement, subsidence measurement, hardness depth measurement.

(2) **Machining error**. When measuring the hardening depth of the workpiece, the workpiece is cut and touched. In the process of processing, the workpiece is deformed by the cutting heat and friction heat, which leads to the generation of errors. In addition, although the dot is operated according to certain rules, it still has certain randomness, which may lead to errors in the measurement of hardening depth.

It is a reasonable and flexible method to use statistics to describe, summarize and explore the distribution law of data and explain the scientific nature of data. It is also a means to fully extract experimental information and deeply reveal the objective law of things. Therefore, this paper will use statistics to deduce the constitutive equation of ZGMn18 high manganese steel.

Without considering the temperature change (at room temperature) and the strain rate as the reference strain rate $\varepsilon_0 = 10^{-3} s^{-1}$, Equation (1) can be reduced to:

$$\sigma = \left[A + B\varepsilon^n\right]\left[1 + C\ln\dot{\varepsilon}^*\right] \tag{2}$$

When the strain rate $\dot{\varepsilon}$ is equal to the reference strain rate $\dot{\varepsilon}_0$, there is $\ln\dot{\varepsilon}^* = 0$, then equation (2) can be converted into:

$$\sigma = A + B\varepsilon^n \tag{3}$$

Where, A is the yield stress of the material when $\varepsilon = 0$ (refers to the plastic strain). Take the logarithm of both ends of Equation (3) and substitute $\ln(\sigma - A) = y$, $\ln B = x$, into equation (3) to get.

$$y = x + nln\varepsilon \tag{4}$$

According to the principle of least square method, the condition that $\dot{y}_i$ can best react y_i is that the sum of squares of residuals has a minimum value, namely:

$$Q_{min} = min\sum_{i=1}^{N}\left(\dot{x} + \dot{n}\ln\varepsilon_i - y_i\right)^2 \tag{5}$$

Then take the partial derivative of Q_{min} with respect to $\dot{x}$ and $\dot{n}$ respectively and equal to zero, the solution is *A* = 315, *B* = 683, *n* = 0,412.

The relationship curve between stress and equivalent plastic strain of high manganese steel at strain rate $\varepsilon_0 = 10^{-3} s^{-1}$ is fitted and compared with the experimental curve. The comparison between linear regression results and experimental data is shown in Figure 2. It can be seen from the figure that the fitting data is in good agreement with the experimental data, which indicates the correctness of the fitting data.

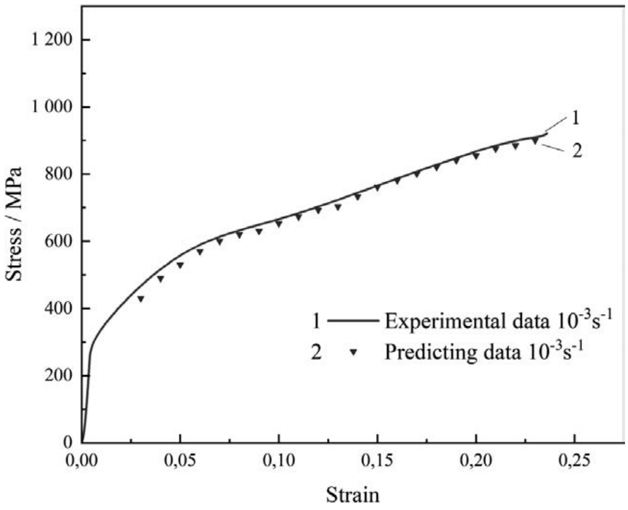

Figure 2 $10^{-3}s^{-1}$Comparison of experimental data and predicting data

The treatment of parameter C is the same as that of parameter B. Since C in the second item describes the strain rate effect of materials, it is taken as a function of strain rate.

Without considering the temperature change and when ε = 0, the relationship between yield stress and strain rate of ZGMn18 at normal temperature can be obtained from Equation (1).

$$\sigma = A\left(1 + C\ln\dot{\varepsilon}^*\right) \tag{6}$$

Let $y = (\sigma / A) - 1$, substitute it into equation (6) to get:

$$y = C\ln\dot{\varepsilon}^* \tag{7}$$

According to the principle of least square method, the condition that $\dot{y}_i$ can best react y_i is that the sum of squares of residuals has a minimum value, namely:

$$Q_{min} = min\sum_{i=1}^{N}\left(C\ln\dot{\varepsilon}_i^* - y_i\right)^2 \tag{8}$$

Formula (8) can be obtained after sorting out:

$$\dot{C} = \frac{\sum y_i \cdot \ln\dot{\varepsilon}_i^*}{\sum\left(\ln\dot{\varepsilon}_i^*\right)^2} \tag{9}$$

Select the initial yield point data $\dot{\varepsilon}_0 = 10^{-2} s^{-1}$, $\sigma_y = 325{,}13$ MPa, $\dot{\varepsilon}_0 = 10^{-1} s^{-1}$, $\sigma_y = 463{,}38$ MPa, and get C= 0,032.

In summary, Johnson-Cook constitutive model parameters are obtained:

Table 1 **Johnson-Cook model material constants of ZGMn high manganese steel**

A	*B*	*n*	*C*
315	683	0,412	0,032

SIMULATION PREDICTION AND VERIFICATION OF CONSTITUTIVE MODEL

By substituting the above data into equation (1), the constitutive equation of ZGMn18 high manganese steel can be written as follows:

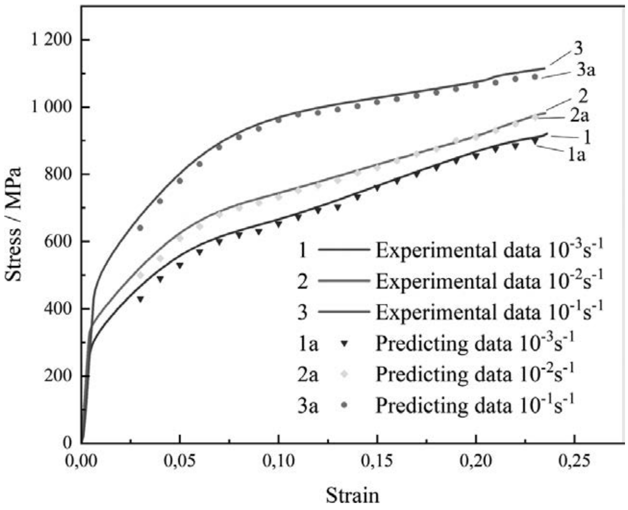

Figure 3 The predicting data was compared with the experimental value

$$\sigma = \left(315 + 683\varepsilon^{0,412}\right)\left(1 + 0,032\ln\dot{\varepsilon}^{*}\right) \tag{10}$$

This model is used to predict the flow stress at different strain rates, and the results are compared with the experimental data, as shown in Figure 3:

CONCLUSION

In this paper, the Johnson-Cook constitutive model of ZGMn18 high manganese steel is deduced by the static compression experiment of ZGMn18 high manganese steel at room temperature. By comparison, the predicted results of the constitutive model are close to the experimental results. The Johnson-Cook constitutive model of ZGMn18 high manganese steel can accurately describe the plastic behavior of the material, which has certain guiding significance for improving the simulation results of cutting high manganese steel. With the further refinement of simulation model structure, the cutting simulation can be closer to the actual machining.

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Note: The responsible translator for English language is X. W. Cheng-
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