Z. L. ZHAO, H. C. JI, J. M. ZHAO, B. X. LIU, W. C. PEI

ISSN 0543-5846
METABK 61(3-4) 721-724 (2022)
UDC – UDK 669.295:531.2-621.979:620.16/539.373-513.6:536.9:621.72=111

JOHNSON-COOK MODEL FOR TC4 TITANIUM ALLOY BASED ON COMPRESSION EXPERIMENT

Received – Primljeno: 2021-11-22
Accepted – Prihvaćeno: 2022-04-10
Original Scientific Paper – Izvorni znanstveni rad

To obtain the exact mechanical properties of TC4 titanium alloy, the compression experiments on TC4 titanium alloy at different strain rates (10^{-2},10^{-3},10^{-4} s^{-1}) were performed at room-temperature on the MTS-810 electrohydraulic servo material testing machine. The data of TC4 titanium alloy compression experiments at different rates were obtained. And furthermore Johnson-Cook constitutive model is established. Due to different conditions, the equation is simplified, the constitutive parameters are obtained by step-by-step estimation method, and the Johnson-Cook (JC) constitutive model of TC4 titanium alloy at room temperature is established. The prediction results of the model were compared with the experimental data, the prediction curve is in good agreement, which verifies the feasibility of the model.

Keywords: TC4 titanium alloy; compression test; stress-strain curves; temperature; Johnson-Cook constitutive model

INTRODUCTION

With the rapid development of science and technology, the demands on materials, especially metals, are increasing in all fields of industrialization. An understanding of its performance under extreme conditions is required to fully and effectively exploit the material's potential [1]. Titanium alloy has the advantages of light mass, high specific strength, good corrosion resistance, high thermal strength and good low temperature performance. It is widely used in high-tech fields such as aerospace, navigation, military and national defense [2]. The main components of titanium alloys are α-phase, β-phase titanium alloys and α+β two-phase titanium alloys. Two-phase titanium alloys are the most widely used of these, with TC4 being the most representative. Due to the unique processing of titanium alloys, the yield is approximately 50 %, so it is important to understand the mechanical properties of TC4 titanium alloys. Many alloys will have different mechanical properties under different loading conditions.

Due to the high sensitivity to strain rate and temperature loading conditions, the dynamic mechanical properties of titanium alloys at high strains are very different compared to those at quasi-static conditions [3]. The deformation characteristics of materials under different loading conditions have been studied by many researchers over the last few decades. Many constitutive models have been proposed or modified to describe the flow behavior. These models can be divided into three main categories: empirical constitutive models, semi-empirical constitutive models and physically based constitutive models. However, this requires a lot of experimental data, including the Johnson-Cook model, the Zerilli-Armstrong model, the Steinberg-Guina model and the Cowper-Symonds model. Where the Johnson-Cook constitutive model involves fewer material constants, it can be called up directly in many finite element software and is widely used to predict the mechanical properties of materials. The current Johnson-Cook model includes 5 material constants. The model takes into account strain-rate hardening and thermal softening effects. Because of its simple expression and, good adaptability, clear physical interpretation and easy access to material parameters, it is one of the most popular metal characterization composition models [5]. The Johnson-Cook model is suitable for describing the dynamic behavior of metallic materials from low to high strain rates, and can even be used for quasi-static deformation analysis [6].

For the mechanical properties and constitutive relationship of TC4 titanium alloy, many people have carried out research at present. However, due to the test equipment and test methods, studies have been conducted mainly in the quasi-static (10^{-4}~10^{-2} s^{-1}) and high strain rate (10^{2}~10^{4} s^{-1}) range of the material [7]. Chen Gang et al, studied the dynamic constitutive model of TC4 titanium alloy by using the results of quasi-static high temperature test and Hopkinson compression bar test (SHPB), and fitted the Johnson cook constitutive model [8]. Regarding the low (10^{-2}~10^{-1} s^{-1}) and medium strain rate (10^{-1}~10^{2} s^{-1}) mechanical properties of the material, Huh et al, investigated the fitting characteristics of various well-known intrinsic structure models using electronic universal testing machines, high-speed

Z. L. Zhao, H. C. Ji (E-mail: jihongchao@ncst.edu.cn), J.M. Zhao, B.X. Liu, W.C. Pei, College of Mechanical Engineering, North China University of Science and Technology, Hebei, Tangshan, China.

hydraulic servo testing machines and SHPB devices. Using these devices, the fitting properties of multiple well-known constitutive models are studied in a range of low, moderate and high strain rates and verified by testing at a large range of strain rates. The results show that the yield stress of Ti-6Al-4V is approximately linearly related to the logarithmic strain rate. Compared to other models the Johnson-Cook standard model, it can better describe the mechanical properties of materials with low, medium and high strain rates [9].

The above studies show that there has been a great deal of research into the dynamic mechanical properties of TC4 titanium alloys, covering high, medium and low strain rate mechanical properties of materials. The Johnson-Cook constitutive model is widely used in the construction of dynamic constitutive models of materials because of its simplicity and easy accessibility. However, the mechanical properties under quasi-static conditions at room temperature are less studied. The constitutive model of TC4 titanium alloy under quasi-static conditions at room temperature is missing, and the mechanical properties of TC4 titanium alloy under quasi-static conditions cannot be obtained. In this paper, the Johnson-Cook constitutive model of TC4 titanium alloy is fitted based on the stress-strain curves for different strain rates (10^{-2} s^{-1},10^{-3} s^{-1},10^{-4} s^{-1}) at quasi-static room temperature. The relevant constitutive parameters of the material were obtained, and the prediction curves obtained by comparing the model predictions with the experimental data fit well.

QUASI-STATIC COMPRESSION EXPERIMENT

TC4 titanium alloy is a medium strength α+β two phase titanium alloy. Due to its good overall mechanical properties, which has been used widely in many fields. The chemical composition of TC4 titanium alloy is in Table 1.

The quasi-static compression test was carried out on the MTS-810 electro-hydraulic servo material testing machine. The principle of the test is shown in Figure 1.

Table 1 **Chemical compositions of TC4 alloy / wt. %**

Al	V	Fe	C	N	H	O	Ti
5,50~6,75	3,5~4,50	0,30	0,10	0,05	0,015	0,20	Bal

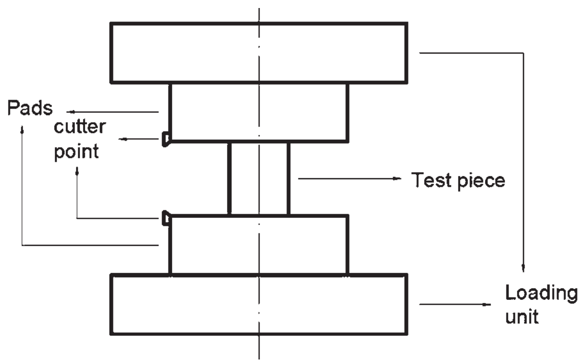

Figure 1 Schematic diagram of quasi-static compression experiments

The specimen is sandwiched between two stronger pads at the top and bottom. The strain and strain rate are measured and controlled by a lead gauge between the two cutters. The matting material has a high strength and is essentially free from plastic deformation.

TEST DATA AND CONSTITUTIVE MODEL ESTABLISHMENT

The Johnson-Cook constitutive is an empirical constitutive model proposed by Johnson and Cook in 1993 for the problems of high-speed impact and explosive penetration to describe the strain rate strengthening effect and temperature softening effect of metals. They established an empirical yield function that describes the plastic flow of metal materials under dynamic load:

$$\sigma_y = \left(A + B\varepsilon_p^n\right)\left(1 + C\ln\dot{\varepsilon}^*\right)\left(1 - T^{*m}\right) \tag{1}$$

A, B, n, C and m are material parameters: ε_p is the equivalent plastic strain; $\dot{\varepsilon}^* = \dot{\varepsilon}_p / \dot{\varepsilon}_0$ is the dimensionless equivalent plastic strain rate; $\dot{\varepsilon}_0$ is the reference strain rate; $T^* = \left(T - T_r\right)/\left(T_m - T_r\right)$ is the dimensionless temperature where is the reference temperature (generally taken as room temperature) and T_m is the material melting point temperature.

The key to building the Johnson-Cook constitutive model for TC4 titanium alloy is to estimate the material parameters in the model based on the data available. The method of parameter estimation in this paper is to estimate the material parameters separately in a certain sequence according to the physical meaning of the parameters that called the stepwise estimation method.

The deformation behavior of TC4 titanium alloy at quasi-static different strain rates at room temperature was tested and the stress-strain curve of TC4 titanium alloy was obtained as shown in Figure 2.

For the Johnson-Cook constitutive model, it means that decoupling the hardening effect, the strain rate effect and the temperature softening effect in the constitutive equation, fixing two of these effects separately and

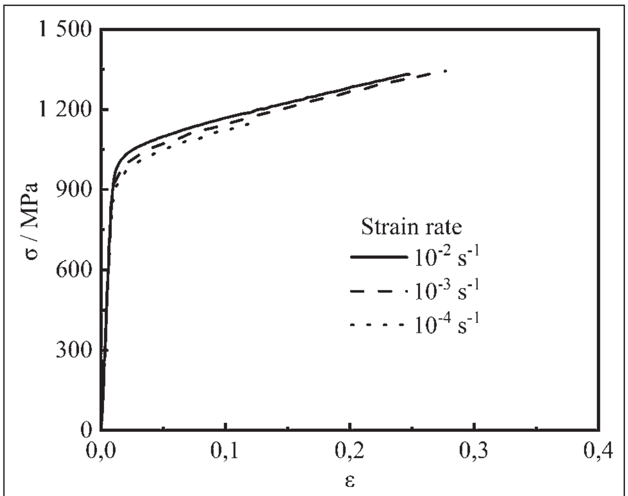

Figure 2 Stress-strain curve of TC4 at different strain rates at room temperature

estimating the material parameters for the other effect from experimental data.

The Johnson-Cook model in Equation (1) contains five material parameters, which are determined sequentially in a certain order by the stepwise estimation method. Since the experimental data were measured at room temperature ($T = T_r$), the equation was simplified without considering the thermal softening effect of the material as follows:

$$\sigma_y = \left(A + B\varepsilon_p^n\right)\left(1 + C\ln\dot{\varepsilon}^*\right) \tag{2}$$

The parameter estimation steps are as follows:

1) Estimation of parameters *A, B,* and *n*

From Equation (2), it can be seen that the parameter *A* is the quasi-static initial yield stress of the material, and *B* and *n* are the hardening factor and index respectively. $\dot{\varepsilon}_0$ of 10^{-3} s^{-1} ($\dot{\varepsilon} = \dot{\varepsilon}_0 = 10^{-3}\,\mathrm{s}^{-1}$) was selected as reference strain rate. The yield Equation (2) can be simplified to a power function form as follows:

$$\sigma_y = A + B\varepsilon_p^n \tag{3}$$

Based on the above equation, the parameter *A* can be determined from the quasi-static stress-strain data for the room temperature reference strain rate case, determining *A* = 869, 658. Deforming both sides of Equation (3) while taking the natural logarithm. It obtains Equation (4):

$$\ln\left(\sigma_y - A\right) = lnB + nln\varepsilon_p \tag{4}$$

The flow stress data of the equivalent plastic strain in the case of *A* values and reference strain rates are brought to $\ln\left(\sigma_y - A\right)$ for fitting.

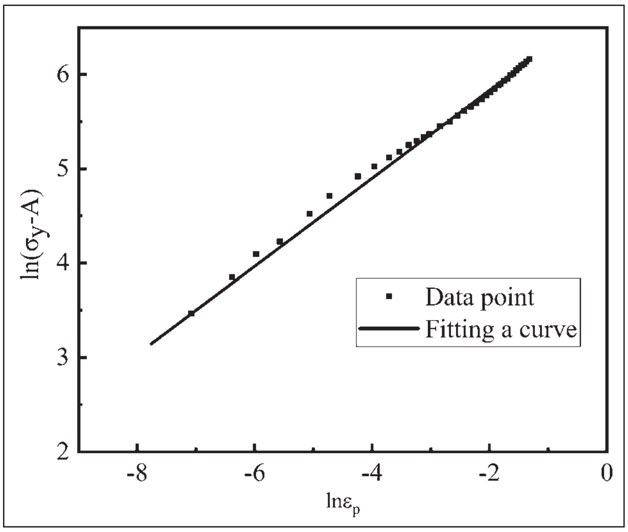

Figure 3 Relation curves of ln(σ_y–*A*) and lnε_p

Figure 3 shows the linear graph fitted by least-square method, with a correlation of 98,8 % for the fitted lines, which indicates that $\ln\left(\sigma_y - A\right)$ and lnε_p have a good linear relationship. The slope of the fitted line is *n* and the intercept is ln*B*. The fitted curve shows *n* = 0, 466 and ln*B* = 6,76, which gives *B* = 862, 642.

2) Estimate parameter *C*

The parameter *C* is the strain rate sensitivity parameter. When the temperature is room temperature, Equation (2) can be changed as follows:

$$\frac{\sigma_y}{A + B\varepsilon_p^n} = 1 + Cln\dot{\varepsilon}^* \tag{5}$$

Where $\dot{\varepsilon}^* = \dot{\varepsilon}_p / \dot{\varepsilon}_0$ is the dimensionless equivalent plastic strain rate, $\dot{\varepsilon}_p$ is the strain rate, $\dot{\varepsilon}_0$ is the reference strain rate. The reference strain rate was chosen as $\dot{\varepsilon}_0 = 10^{-3}\,\mathrm{s}^{-1}$, and points on the other two data sets were selected for the fit. When the initial yield point is chosen, the equivalent plastic deformation is $\varepsilon_p = 0$. Equation (5) was changed as follows:

$$\frac{\sigma_y}{A} - 1 = C\ln\dot{\varepsilon}^* \tag{6}$$

At this time, the intercept distance is 1, and the slope is *C*. The *C* value can be determined by fitting the flow stress at a fixed effective strain at different strain rates.

Select initial yield point data, point a: $\dot{\varepsilon}_0 = 10^{-2}\,\mathrm{s}^{-1}$, $\sigma_y = 970{,}085$; point b: $\dot{\varepsilon}_0 = 10^{-4}\,\mathrm{s}^{-1}$, $\sigma_y = 880{,}342$. Points a and b are fitted to a straight line by using the least squares method.

Figure 4 shows the linear graph obtained from the least-square method fit to obtain the slope of the fitted line, *C* = 0, 022.

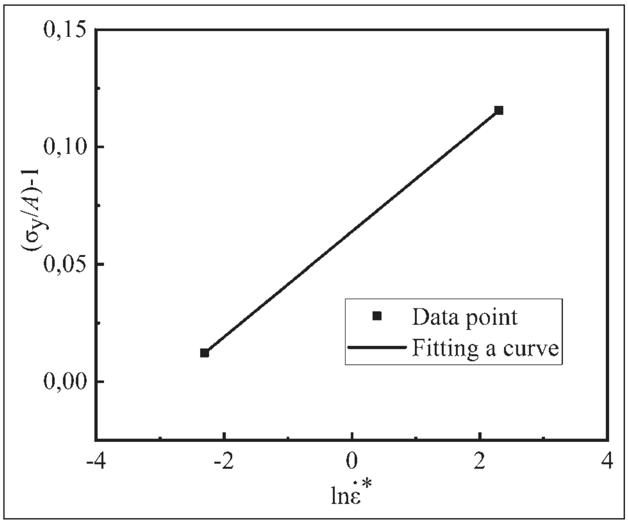

Figure 4 Relation curves of (σ_y/*A*) and ln$\dot{\varepsilon}$*

In summary, the Johnson-Cook constitutive model parameters are obtained in Table 2.

Table 2 **Material parameter of Johnson-Cook model**

Parameters	*A* / MPa	*B* / MPa	*n*	*C*
Stepwise estimation method	869,66	862,64	0,47	0,02

PREDICTION AND VERIFICATION OF CONSTITUTIVE MODEL SIMULATION

Putting the model parameters obtained above into Equation (2), the Johnson-Cook constitutive model of TC4 titanium alloy at room temperature can be obtained:

$$\sigma_y = \left(869,66 + 862,64\varepsilon_p^{0,47}\right)\left(1 + 0,02\ln\dot{\varepsilon}^*\right) \qquad (7)$$

The equation was used to predict the flow stress at different strain rates, and the obtained predicted data were compared with experimental data.

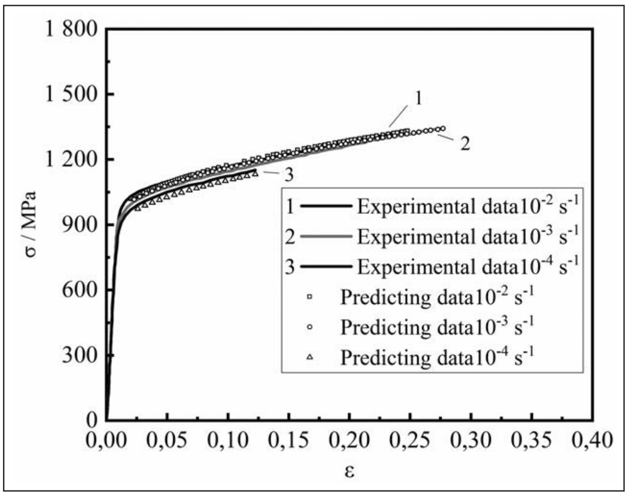

Figure 5 Predicted values were compared with experimental values

Figure 5 shows the curve comparing the predicted and experimental values of the Johnson-Cook constitutive model. It can be seen that the predicted values of the Johnson-Cook constitutive model have a good fit with the experimental values.

CONCLUSION

This paper investigates the intrinsic structure relationship of TC4 titanium alloy material under quasi-static conditions at room temperature. By simplifying the model, the parameters of the Johnson-Cook constitutive model are estimated step by step. The constitutive model of TC4 titanium alloy under quasi-static conditions at room temperature is obtained. Comparison of the predicted data with the experimental data showed a high degree of agreement, which proves that the Johnson-cook constitutive equation established in this paper has high accuracy.

Acknowledgments

This work is supported by the Tangshan talent foundation innovation team (20130204D, 18130216A) and funded by S&P Program of Hebei (Grant No.1901 2204Z).

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Note: The responsible translator for English language is J. Yuan -North China University of Science and Technology, China