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STUDY ON MECHANICAL PROPERTIES OF 6061-T6 ALUMINUM ALLOY

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In order to obtain the accurate mechanical properties of 6061-T6 aluminum alloy, the tensile test of 6061-T6 aluminum alloy was carried out on a high-speed material testing machine, and the tensile test data of 6061-T6 aluminum alloy at different rates were obtained. Then, the Johnson-Cook constitutive model was introduced, and the formula was simplified based on the experimental conditions. The constitutive parameters were obtained by the stepwise estimation method, and the Johnson-Cook (JC) constitutive model of 6061-T6 aluminum alloy was established. Comparing the model prediction results with the experimental data, the prediction curves are in good agreement, which verifies the feasibility of the model.

Keywords: 6061-T6 aluminum alloy; tensile test; stress-strain curves; Johnson-Cook constitutive model

INTRODUCTION

With the rapid development of science and technology, the requirements for materials, especially metal materials, are getting higher and higher in various industrial fields. It is necessary to understand the properties of materials under various extreme conditions to fully and effectively utilize the potential of materials [1]. Aluminum alloy has the advantages of low density, high strength, high plasticity, excellent electrical conductivity, thermal conductivity and corrosion resistance. It is widely used in marine, land, air, machinery manufacturing and chemical industry [2].

When aluminum alloy is used as a structural material, it is inevitable to encounter foreign objects such as impact, extrusion and explosion impact. These behaviors cause serious deformation and even fracture of the aluminum alloy structure. Therefore, it is necessary to study the mechanical properties of aluminum alloy materials at different strain rates.

Due to the high sensitivity to strain rate and temperature loading conditions, the dynamic mechanical properties of aluminum alloy under high strain are very different from those under quasi-static conditions [3]. In the past few decades, many researchers have studied the deformation characteristics of materials under different load conditions, and proposed or modified many constitutive models to describe the flow behavior. These models can be divided into three categories: empirical constitutive model, semi-empirical constitutive model and physics-based constitutive model [4]. For example, Johnson-Cook model, Zerilli-Armstrong model, Steinberg-Guina model and Cowper-Symonds model. Among them, the Johnson-Cook constitutive model involves less material constants and can be directly called in many finite element software, so it is widely used to predict the mechanical properties of materials. The current Johnson-Cook model includes five material constants. This model takes into account the strain rate hardening and thermal softening effects. Because of its simple expression and good adaptability, it has clear physical interpretation and material parameters are easy to obtain. It is one of the most popular metal characterization models [5]. The Johnson-Cook model is suitable for describing the dynamic behavior of metal materials from low strain rate to high strain rate, and can even be used for quasi-static deformation analysis [6].

At present, many people have carried out research on the mechanical properties and constitutive relationship of 6061-T6. However, due to the test equipment and test methods, the research has been carried out mainly in the quasi-static (10^{-4}~$10^{-2}s^{-1}$) and high strain rate (10^{2}~$10^{4}s^{-1}$) range [7]. Bobbili et al. conducted high strain rate compression experiments in the strain rate range of 1 500~4 500 s^{-1}. The results show that the flow stress of 7017 aluminum alloy increases with the increase of strain rate [8]. Liu SD et al. studied the high strain rate deformation behavior and microstructure evolution of 7055 aluminum alloy. In the strain rate range of 1 000 ~ 4 000 s^{-1}, the maximum stress tends to increase, and the strain rate sensitivity is positive. In the strain rate range of 4 000~6 000 s^{-1}, the strain rate sensitivity is negative. This phenomenon is due to shear bands and cracks generated during deformation [9].

The above studies show that there have been a lot of studies on the dynamic mechanical properties of 6061-T6 aluminum alloy, covering the quasi-static and high

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strain rate mechanical properties of materials. Johnson-Cook constitutive model is widely used in the construction of dynamic constitutive model of materials because of its simple and easy to obtain. However, there are few studies on the mechanical properties of 6061-T6 aluminum alloy under strain rate conditions, and there is a lack of mechanical models under this condition. In this paper, the Johnson-Cook constitutive model of 6061-T6 aluminum alloy was fitted according to the stress-strain curve, and the relevant constitutive parameters of the material were obtained. The predicted results of the model were compared with the experimental data, and the predicted curves were in good agreement.

MATERIAL TENSILE TEST

6061-T6 aluminum alloy is prepared by artificial aging after solid solution heat treatment of 6061 aluminum alloy. Its chemical composition is shown in Table 1. The material tensile test was performed on a high-speed material testing machine, as shown in Figure 1.

Table 1 **Chemical compositions of 6061-T6 alloy / wt. %**

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0,4	0,7	0,15	0,15	0,5	0,04	0,25	0,15	Bal

Figure 1 High speed material testing machine

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:

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

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; $T^* = (T - T_r)/(T_m - T_r)$ is the dimensionless temperature where T_r 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 6061-T6 aluminum 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 quasi-static deformation behavior of 6061-T6 aluminum alloy at room temperature at different strain rates was tested, and the stress-strain curve of 6061-T6 aluminum alloy was obtained as shown in Figure 2.

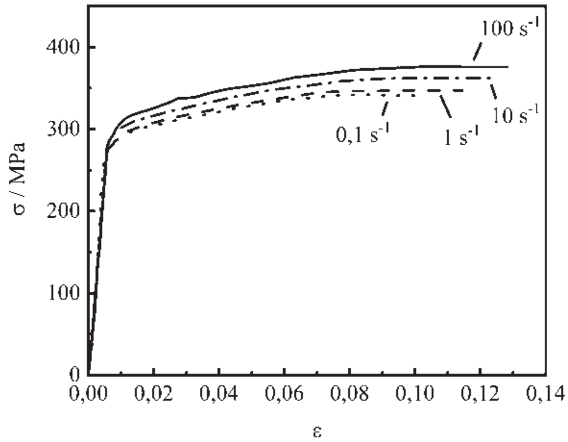

Figure 2 The stress-strain curves of T6061-T6 aluminum alloy at different strain rates at room temperature

The true stress-true strain curve of 6061-T6 aluminum alloy is obtained by substituting the stress-strain curve obtained from the test into Equation (2) and Equation (3), as shown in Figure 3.

$$\sigma_t = \sigma(1 + \varepsilon) \quad (2)$$

$$\varepsilon_t = \ln\ln(1 + \varepsilon) \quad (3)$$

Among them: σ_t is the true stress, ε_t is the true strain; σ is engineering stress and ε is engineering strain.

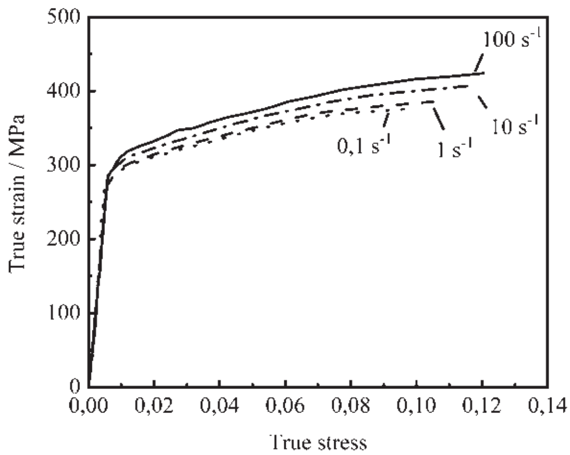

Figure 3 True stress-true strain curve of 6061-T6 aluminum alloy

For the Johnson-Cook constitutive model, the hardening effect, strain rate effect and temperature softening effect in the constitutive equation are decoupled, and the two effects are fixed respectively, and the material parameters of the other effect are estimated according to the 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:

$$\sigma_y = \left(A + B\varepsilon_p^n\right)\left(1 + C\ln\dot{\varepsilon}^*\right) \quad (4)$$

The parameter estimation steps are as follows:

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

From Equation (4), 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 0,1 s^{-1} ($\dot{\varepsilon} = \dot{\varepsilon}_0 = 0{,}1s^{-1}$) was selected as reference strain rate. The yield Equation (4) can be simplified to a power function form as follows:

$$\sigma_y = A + B\varepsilon_p^n \quad (5)$$

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* = 293, 614. Deforming both sides of Equation (5) while taking the natural logarithm. It obtains Equation (6):

$$\ln\left(\sigma_y - A\right) = lnB + nln\varepsilon_p \quad (6)$$

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

Figure 4 shows the linear graph fitted by least-square method, with a correlation of 98, 8 % for the fitted lines, which indicates that $\ln(\sigma_y - A)$ and $\ln\varepsilon_p$ have a good linear relationship. The slope of the fitted line is *n* and the intercept is $\ln\beta$. The fitted curve shows *n* = 0, 741 and $\ln\beta$ = 6,230, which gives *B* = 507, 755.

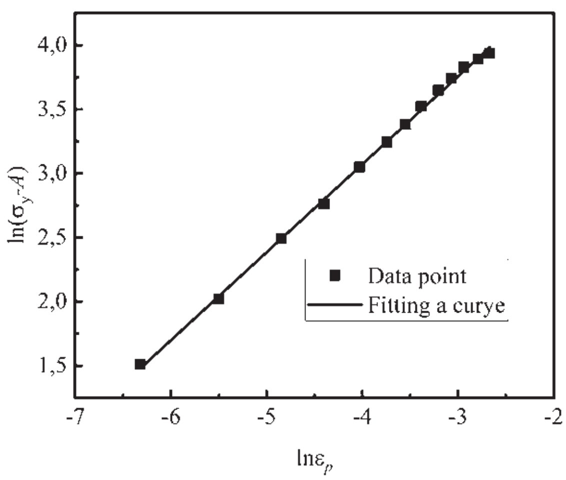

Figure 4 Relation curves of $\ln(\sigma_y - A)$ and $\ln\varepsilon_p$

2) Estimate parameter *C*

The parameter *C* is the strain rate sensitivity parameter. When the temperature is room temperature, Equation (4) can be changed as follows:

$$\frac{\sigma_y}{A + B\varepsilon_p^n} = 1 + Cln\dot{\varepsilon}^* \quad (7)$$

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 $\dot{\varepsilon}_0 = 0.1s^{-1}$, 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 (7) was changed as follows:

$$\frac{\sigma_y}{A} - 1 = C\ln\dot{\varepsilon}^* \quad (8)$$

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.

Figure 5 shows the linear graph obtained from the least-square method fit to obtain the slope of the fitted line, *C* = 0, 011.

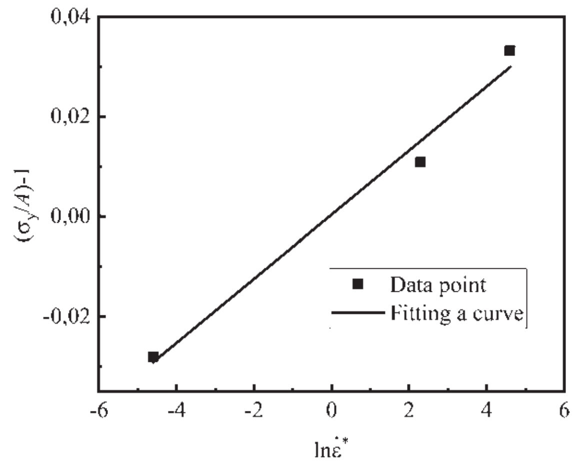

Figure 5 Relation curves of $(\sigma_y/A) - 1$ and $\ln\dot{\varepsilon}^*$

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	293, 614	507, 755	0, 741	0, 011

PREDICTION AND VERIFICATION OF CONSTITUTIVE MODEL SIMULATION

Putting the model parameters obtained above into Equation (4), the Johnson-Cook constitutive model of 6061-T6 aluminum alloy at room temperature can be obtained:

$$\sigma_y = \left(293{,}614 + 507{,}755\varepsilon_p^{0{,}741}\right)\left(1 + 0{,}011\ln\dot{\varepsilon}^*\right) \quad (9)$$

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

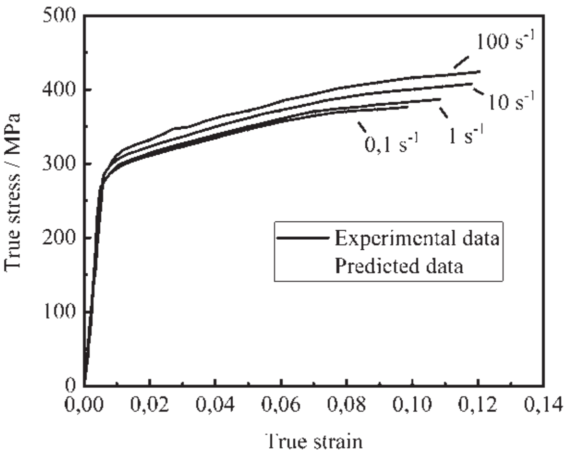

Figure 6 Predicted values were compared with experimental values

Figure 6 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

In this paper, the constitutive relationship of 6061-T6 aluminum alloy at room temperature is studied. By simplifying the model, the parameters of Johnson-Cook constitutive model are gradually estimated, and the constitutive model of 6061-T6 aluminum alloy is obtained. By comparison, the predicted results of the constitutive model are close to the experimental results. The Johnson-Cook constitutive equation established in this paper has high accuracy.

Acknowledgments

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REFERENCES

[1] Z Changqing, X Lansheng, C Minghe, et al. Dynamic mechanical property and plastic constitutive relation of TC4-DT Ti alloy under high strain rate [J]. The Chinese Journal of Nonferrous Metals 25 (2015), 323-329.

[2] Ji H, Ma Z, Huang X, et al. Damage evolution of 7075 aluminum alloy basing the Gurson Tvergaard Needleman model under high temperature conditions [J]. Journal of Materials Research and Technology 16 (2022), 398-415.

[3] Zhao Z, Ji H, Zhong Y, et al. Mechanical Properties and Fracture Behavior of a TC4 Titanium Alloy Sheet [J]. Materials 23 (2022), 8589.

[4] Cai S, Ji H, Zhu F, et al. Research on the Corrosion Behavior of Q235 Pipeline Steel in an Atmospheric Environment through Experiment [J]. Materials 18(2022), 6502.

[5] Peroni L, Scapin M, Fichera C, et al. Investigation of the mechanical behaviour of AISI 316L stainless steel syntactic foams at different strain-rates [J]. Composites Part B: Engineering 66 (2014), 430–442.

[6] Hallquist J O. LS-dyna keyword user′s manual v970. Livermore Software Technology Corporation, California, (2003)

[7] H Xulong, M Rangke, B Chunyu, et al. Dynamic mechanical property and constitutive model for TC4 titanium alloy [J]. Journal of Vibration and Shock 35 (2016), 161-168.

[8] Bobbili R, Ramakrishnav B, Madhu V, et al. Prediction of flow stress of 7017 aluminium alloy under high strain rate compression at elevated temperatures [J]. Defence Technology (2015), 93-98.

[9] Liu S D, Wang S L, Ye L Y, et al. Flow behavior and microstructure evolution of 7055 aluminum alloy impacted at high strain rates [J]. Materials Science and Engineering A, 677(2016), 203-210.

Note: The responsible translator for English language is M.W. LIU - Tiangong University, China