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STUDY ON HOT DEFORMATION BEHAVIOR AND CONSTITUTIVE MODEL OF TB6 TITANIUM ALLOY

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Thermecmaster-Z thermal simulator was used to carry out hot compression experiments on the metal material TB6 titanium alloy of exoskeleton robot at deformation temperature of 1 013 ~ 1 073 K and strain rate of 0,001 ~ 1 s^{-1}, and the influence of deformation conditions on the flow stress of TB6 titanium alloy was studied. The multivariate linear regression constitutive model of TB6 titanium alloy was established by Arrhenius hyperbolic sine equation. The results show that the flow stress is significantly affected by the strain rate, and the influence of deformation temperature on the flow stress is related to the strain rate. The theoretical value of the peak stress obtained by the multiple linear regression constitutive model of TB6 titanium alloy is well fitted with the actual value, and the correlation reaches 98,11 %, which proves that the model has high prediction accuracy.

Keyword: TB6 titanium alloy, hot deformation behavior, true stress-true strain curve, constitutive model, deformation activation energy

INTRODUCTION

TB6 titanium alloy has the advantages of high specific strength, good fracture toughness and strong stress corrosion resistance, and is often used in the lightweight design and manufacture of exoskeleton robots[1]. However, the thermal processing technology of TB6 titanium alloy is complex, and the microstructure uniformity after forging is poor, which seriously affects its mechanical properties. The hot deformation behavior is the basis for formulating its hot working process[2]. The microstructure and properties of TB6 titanium alloy after hot deformation depend on the interaction of work hardening and dynamic softening during hot deformation. Therefore, it is of great significance to study the thermal deformation behavior and establish the constitutive model for the study of material properties and hot forming process[3].

In order to explore the relationship between strain rate, deformation temperature and flow stress, the high temperature compression experiment of TB6 titanium alloy was carried out by Thermecmaster-Z thermal simulator, and the variation characteristics of flow stress-strain rate curve were studied. The constitutive model was established by Arrhenius hyperbolic sine method based on the calculation of material parameters such as deformation activation energy. Finally, The experimental data are compared with the model prediction data to verify the accuracy of the constitutive model.

Hot compress test

The chemical composition of TB6 titanium alloy used in the experiment is : 0,1048 V, 0,0174 Fe, 0,0252 Al, residual Ti. The β phase transition temperature is 790 ~ 805 °C. The blank is processed into a cylindrical sample of $\phi 8\ mm \times 12\ mm$. The sample was placed on the Thermecmaster-Z thermal simulator for compression test. The deformation temperature was 1 013, 1 033, 1 053, 1 073 K, the heating rate was $283{,}15 K \cdot s^{-1}$, the strain rate was 0,001, 0,01, 0,1, 1 s^{-1}, and the true strain was 0,7.The real-time temperature of the sample was measured by thermocouple in the middle of the side of the sample, and the temperature of the sample was controlled within the range of ± 1 °C of the deformation temperature. The compressed sample was cooled to room temperature in fluorine gas.

Experimental data

The true stress-true strain curves of TB6 titanium alloy during hot compression deformation at different temperatures were obtained by experimental test, as shown in Figure 1. It can be seen from the experimental results curve. With the increase of deformation temperature and the decrease of strain rate, the flow stress of the alloy decreases. At the same deformation temperature, the flow stress of the alloy increases with the increase of the strain rate, and the peak strain required for the flow stress of the alloy to reach the peak stress increases. It shows that the time of dynamic softening mechanism as the main deformation mechanism is delayed. At the same strain rate, the flow stress decreases

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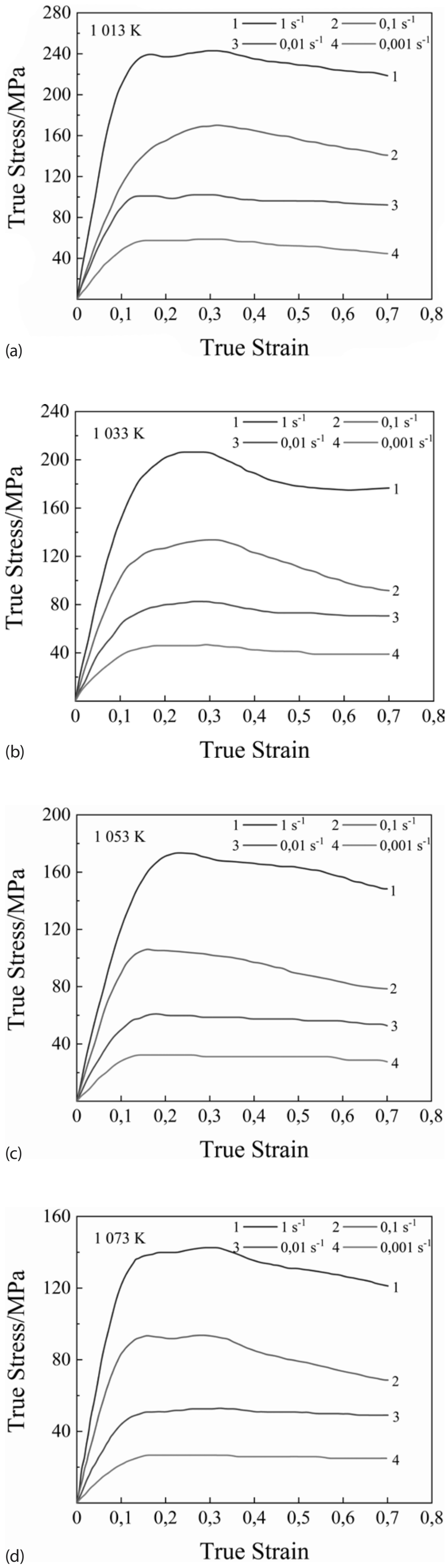

Figure 1 True stress-true strain curves at different compression temperatures

with the increase of deformation temperature. However, the effect of temperature on the flow stress is related to the strain rate. The greater the strain rate, the more significant the effect of temperature on the flow stress.

Construction of constitutive model

According to the Arrhenius equation, the temperature-compensated strain rate Zener-Hollnmon parameter was introduced to compensate the strain rate to construct the Arrhenius-type constitutive model. During the deformation process of TB6 titanium alloy, the constitutive relation expressions of different stress zones are as follows :

$$\dot{\varepsilon} = A_1 \sigma^{n_1} \exp\left(\frac{-Q}{RT}\right), \quad \alpha\sigma \leq 0,8 \tag{1}$$

$$\dot{\varepsilon} = A_2 \exp(\beta\sigma) \exp\left(\frac{-Q}{RT}\right), \quad \alpha\sigma \geq 1,2 \tag{2}$$

In the formula: R is the molar gas constant, the value is 8,314 J · (mol/K)$^{-1}$, A_1, A_2, α, n is the material constant, σ is the true stress, T is the deformation temperature (K), Q is the thermal deformation activation energy (J / mol).

Therefore, the relationship between flow stress σ, temperature T and strain rate $\dot{\varepsilon}$ at any stress level can be expressed as:

$$\dot{\varepsilon} = A\left[\sinh(\alpha\sigma)\right]^n \exp\left(\frac{-Q}{RT}\right), \quad \text{Any stress level} \tag{3}$$

The logarithm of (1) and (2) can be obtained:

$$In\dot{\varepsilon} = InA_1 + n_1 In\sigma - \frac{Q}{RT} \tag{4}$$

$$In\dot{\varepsilon} = InA_2 + \beta\sigma - \frac{Q}{RT} \tag{5}$$

Under the condition of constant temperature, σ is taken as the peak stress, and the logarithm of σ is taken to obtain ln σ, which is brought into Eqs. (4) and (5) to obtain ln $\dot{\varepsilon}$. The coordinates of σ and ln $\dot{\varepsilon}$ are plotted, as shown in Figure 2. The slope of each straight line was obtained by linear regression analysis of the least square method, and the slope was averaged to obtain k_1 = 0,04737.

Figures are plotted with ln σ and ln $\dot{\varepsilon}$ as coordinates, as shown in Figure 3. The slope of each straight line was obtained by least square linear regression analysis, and the average slope was k_2 = 4,1111075. According to Formula $\alpha = k_1 / k_2$, α = 0,011522 MPa^{-1} is obtained.

The logarithm of pair (3) can be obtained:

$$In\dot{\varepsilon} = InA + nIn\left[\sinh(\alpha\sigma)\right] - \frac{Q}{RT} \tag{6}$$

Then the partial derivative transformation of the pair (3) is carried out respectively to obtain:

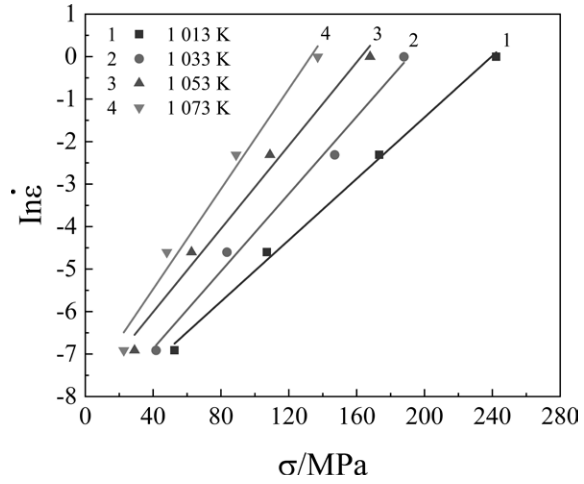

Figure 2 Relation curves of ln $\dot{\varepsilon}$ and σ

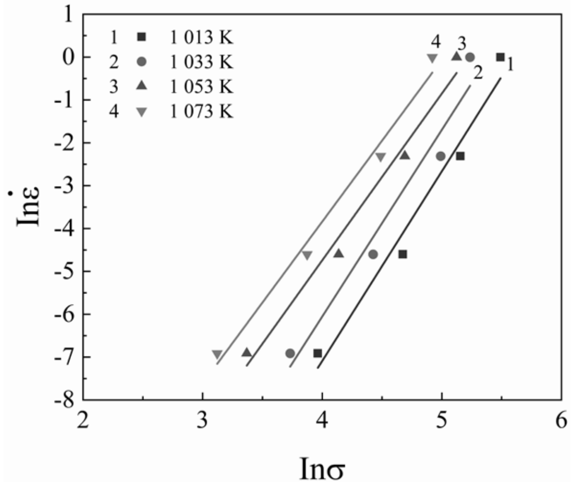

Figure 3 Relation curves of ln $\dot{\varepsilon}$ and ln σ

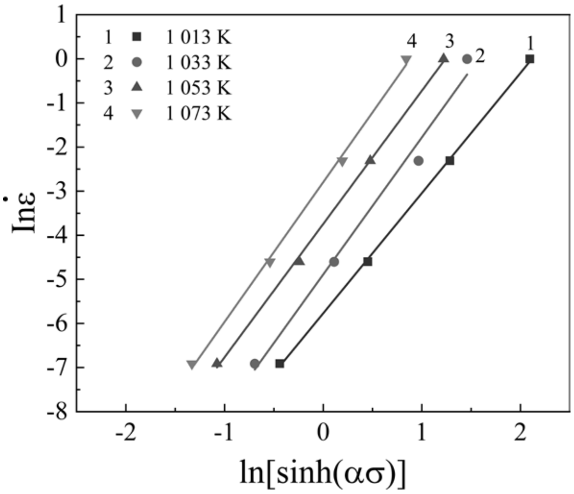

Figure 4 Relation curves of ln $\dot{\varepsilon}$ and ln[sinh($\alpha\sigma$)]

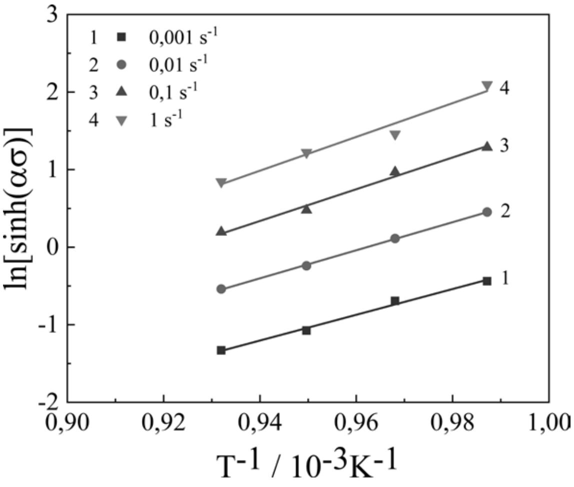

Figure 5 Relation curves of ln[sinh($\alpha\sigma$)] and 1/T

$$n = \frac{\partial In\dot{\varepsilon}}{\partial In\left[\sinh\left(\alpha\sigma\right)\right]} \tag{7}$$

$$K = \frac{Q}{nR} = \frac{\partial In\left[\sinh\left(\alpha\sigma\right)\right]}{\partial\left(1/T\right)} \tag{8}$$

Where K is the material constant.

The value of ln[sinh($\alpha\sigma$)] is obtained according to α and σ, and the coordinates of ln[sinh($\alpha\sigma$)] and ln $\dot{\varepsilon}$ are plotted, as shown in Figure 4. The slope of each straight line was obtained by linear regression analysis of the least square method, and the average value of the slope of the regression straight line was calculated to be n = 3,006103.

Under the condition of keeping the strain rate constant, the coordinates of ln[sinh($\alpha\sigma$)] and 1/T are plotted, as shown in Figure 5. The slope of each straight line was obtained by linear regression analysis of the least square method, and the average value of the slope of the regression straight line was calculated to be K = 19 232,437.

According to Eq. (8), the calculation formula of thermal activation energy Q is obtained, and the expression is as follows:

$$Q = R\frac{\partial In\left[\sinh\left(\alpha\sigma\right)\right]}{\partial\left(1/T\right)} \cdot \frac{\partial In\dot{\varepsilon}}{\partial In\left[\sinh\left(\alpha\sigma\right)\right]} = nRK \tag{9}$$

According to formula (9), Q = 480 672,14 J/mol is calculated.

According to the definition of hyperbolic sine function, σ can be expressed as a function of Zener-Hollomon parameter Z:

$$Z = \dot{\varepsilon}\exp(\frac{Q}{RT}) = A[\sinh(\alpha\sigma)^n] \tag{10}$$

The logarithm of pair (10) can be obtained:

$$\ln Z = n\ln[\sinh(\alpha\sigma)] + \ln A \tag{11}$$

According to formula (11), ln Z is obtained, and ln Z and ln[sinh($\alpha\sigma$)] are used as coordinates for drawing, as shown in Figure 6. Linear regression processing was performed on the data graph, and finally the intercept ln A = 51,10539 was obtained, and then the structural factor $A = 1{,}56599 \times 10^{22}$ of the experimental alloy TB6 was obtained.

The calculated 1, 2, 3, and 4 are brought into Formula (3), and the peak stress constitutive equation is obtained as follows:

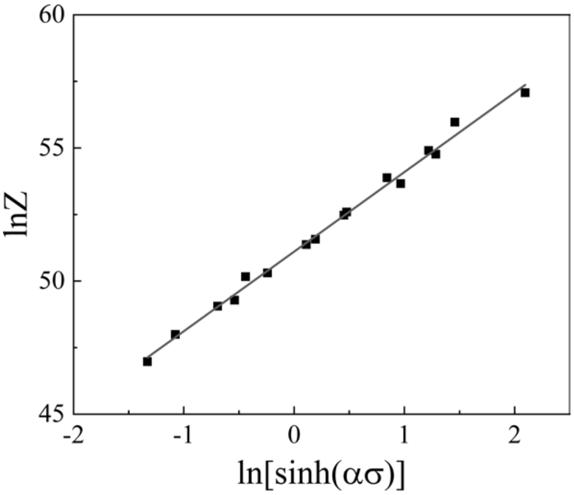

Figure 6 Relation curves of ln*Z* and ln[sinh(*ασ*)]

$$\dot{\varepsilon} = 1,56599\times10^{22}\left[\sinh(0,011522\sigma)\right]^{3,006103}\exp\left(\frac{-480\ 672,14}{8,314T}\right) \quad (12)$$

Simulation prediction and verification of constitutive model

In order to test the applicability and accuracy of the Arrhenius constitutive model of TB6 titanium alloy, the calculated values of flow stress obtained by the constitutive model of TB6 titanium alloy are compared with the experimental values, as shown in Figure 7. The correlation coefficient between the calculated results of the constitutive model of TB6 titanium alloy and the experimental values is 98,18 %. Indicating that the established constitutive model of TB6 titanium alloy has high calculation accuracy for flow stress.

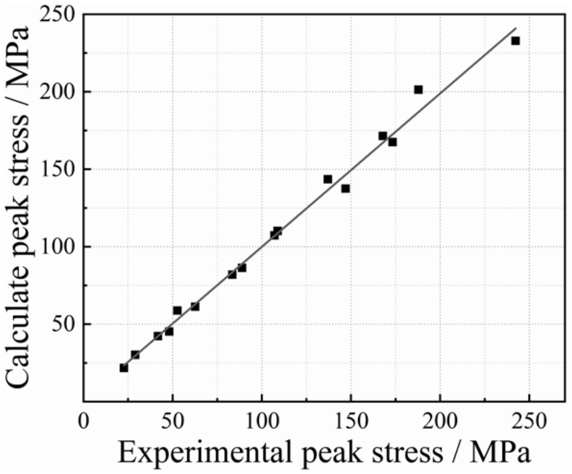

Figure 7 The peak stress calculation results are compared with the measured values

CONCLUSION

(1) The flow stress of TB6 titanium alloy during hot compression deformation is significantly affected by the strain rate, and the influence of deformation temperature on the flow stress is related to the strain rate.

(2) During hot compression deformation of TB6 titanium alloy, the flow stress is linear with the reciprocal of deformation temperature, and the steady-state flow stress can be described by the exponential form of Z parameter. There is a linear relationship between the natural logarithm of stress and strain rate.

(3) The accuracy and feasibility of the constitutive model of TB6 titanium alloy to predict the flow stress are analyzed and verified. The error between the calculated value of the flow stress obtained by the constitutive model and the experimental value is small, and the prediction accuracy is high.

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