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Study on Hot Deformation Behavior and Constitutive Model of TNTZ Alloy

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Abstract. The isothermal constant strain rate compression experiment of Ti-29Nb-13Ta-4.6Zr (TNTZ) alloy with deformation temperature of 700~900℃ and strain rate of 0.001~1s^{-1} was carried out by Gleeble-3500 thermal simulator. The high temperature deformation behavior of the alloy was discussed and the thermal deformation activation energy was calculated. The hyperbolic sinusoidal constitutive model of TNTZ alloy was constructed. The results show that the flow stress of the alloy tends to be steady at high temperature and low strain rate. The constitutive model established by the Arrhenius model and modified by Zener-Hollomon parameter, which its correlation coefficient R and the average relative error E is 0.971 and 5.92%. The results predicted value for high temperature deformation behavior and agrees well with the experimental value of the alloy.

1. Introduction

TNTZ alloy is one of the new medical β-type titanium alloy Ti-Nb-Zr-Ta series and its wear resistance, biocompatibility and its elastic mode is significantly lower than that of α+β type titanium alloy, which has significantly effect in biomedical applications, such as bone repair and artificial joints [1]. In recent years, many scholars have carried out research on the properties of the alloy. Huang et al [2] prepared a TNTZ alloy with good comprehensive performance by spark plasma sintering, and studied the sintering temperature of the alloy. The effects of structure and mechanical properties. Ye [3] studied the effects of rolling annealing process on the high temperature deformation behavior and hot working process of TNTZ and determined that the rolling treatment can effectively reduce the elastic modulus and improve the strength. In addition, the annealing time, rolling ratio and the influence of $(Ti,Zr)_2Si$ make the elastic modulus and plasticity of the alloy significantly improved and the elastic modulus (24.4-28.9GPa) matching the human skeleton can be obtained. Therefore, TNTZ is widely used in human prostheses and joints.

In this paper, the true stress-true strain curve characteristics of the TNTZ alloy at a temperature of 700℃ to 900℃ and a strain rate of 0.001s^{-1} to 1s^{-1} is analyzed and the traditional Arrhenius model was established to study the constitutive relation. By comparing the predicted stress value and the experimental stress value, the applicability of the model was corrected, which could provide a theoretical basis for the subsequent thermal processing.

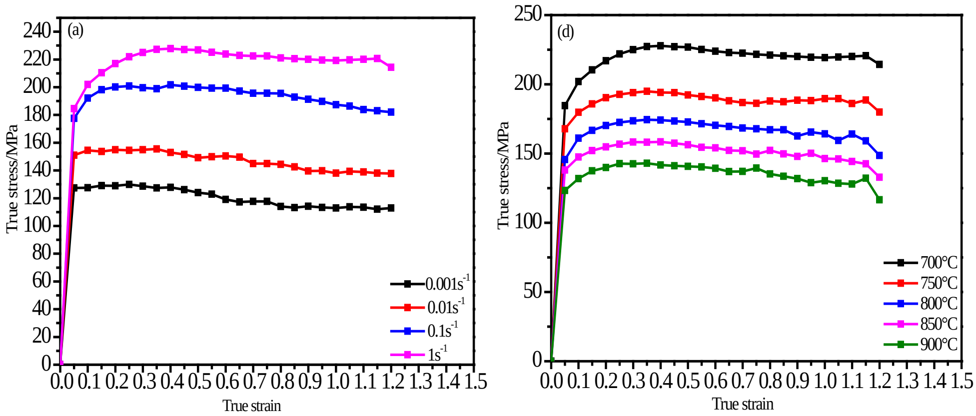
2. Materials and Methods

The experimental material is TNTZ alloy and its nominal composition is Ti-29Nb-13Ta-4.6Zr (at %), the α+β→β phase transformation temperature of the alloy is 850℃. The compressed sample was a cylinder of Φ8 mm×12 mm and an isothermal constant strain rate compression experiment was performed using a Gleeble-3500 thermal simulator. The experimental schemes are: deformation temperatures of 700, 750, 800, 850, 900°C and strain rates of 0.001, 0.01, 0.1, 1.0s^{-1}. The height reduction ratio is 70% and the corresponding true strain is about 1.2. The sample was heated to a deformation temperature at a rate of 10°C /s and then held for 300s to make the temperature uniform. After the end of compression, spray water to cool to room temperature immediately. During compression, the device automatically records true stress-true strain data.

3. Results

3.1. Flow Stress Analysis

Figure 1 shows the true stress of TNTZ alloy about a deformation temperature of 700°C at a strain rate of 0.001s^{-1} to 1.0s^{-1} and a strain rate of 1.0s^{-1} at a deformation temperature of 700~900°C true strain curve. It can be seen from Figure 1(a) that when the deformation temperature is constant, the increase of the strain rate causes an increase in the flow stress. From Figure 1(b), when the strain rate is constant, the increase of the deformation temperature causes the decline of the flow stress. The main reason is when the deformation temperature increases, the atomic diffusion rate of the metal increases and the deformation energy storage effect of the metal causes dynamic softening, thereby reducing the flow stress [4].



(a)T=700°C （b） $\dot{\varepsilon}$ =1.0s^{-1}

Figure 1. TNTZ Alloy True Stress-true Strain Curve

3.2. Establishment and Verification of Constitutive Relationship Model

For different materials, the constitutive relations reflecting the dynamic properties of the materials vary greatly. The relationship of flow stress, strain rate and deformation temperature can be obtained by Zener-Hollomon parameter (Hereinafter referred to as Z-parameter)[5].To optimize the Arrhenius type equation description, the equation has three representations:

$$\dot{\varepsilon}\exp(\frac{Q}{RT}) = A_1\exp(\beta\sigma) \tag{1}$$

$$\dot{\varepsilon}\exp(\frac{Q}{RT}) = A_2\sigma^{n_1} \tag{2}$$

$$\dot{\varepsilon}\exp(\frac{Q}{RT}) = A_3[\sinh(\alpha\sigma^{n})] \tag{3}$$

Where σ is the flow stress(MPa); $\dot{\varepsilon}$ is the strain rate(s^{-1}); Q is the deformation activation energy(kJ/mol); T is the absolute deformation temperature(K); A_1, A_2, A_3, α, β are material constants; n, n_1 is a work hardening constant, where $\alpha = \beta/n_1$. The above equations (1) to (3) are exponential function equations, power function equations and hyperbolic sine function equations. The deformation process of the material can be well described [6].

Logarithmically on both sides of equations (1), (2) and (3) can be derived, as shown in Figure 2 the fitting slope $1/n_1$, $1/\beta$ and get α=0.008841448242728. Equation (3) can be transformed into the following:

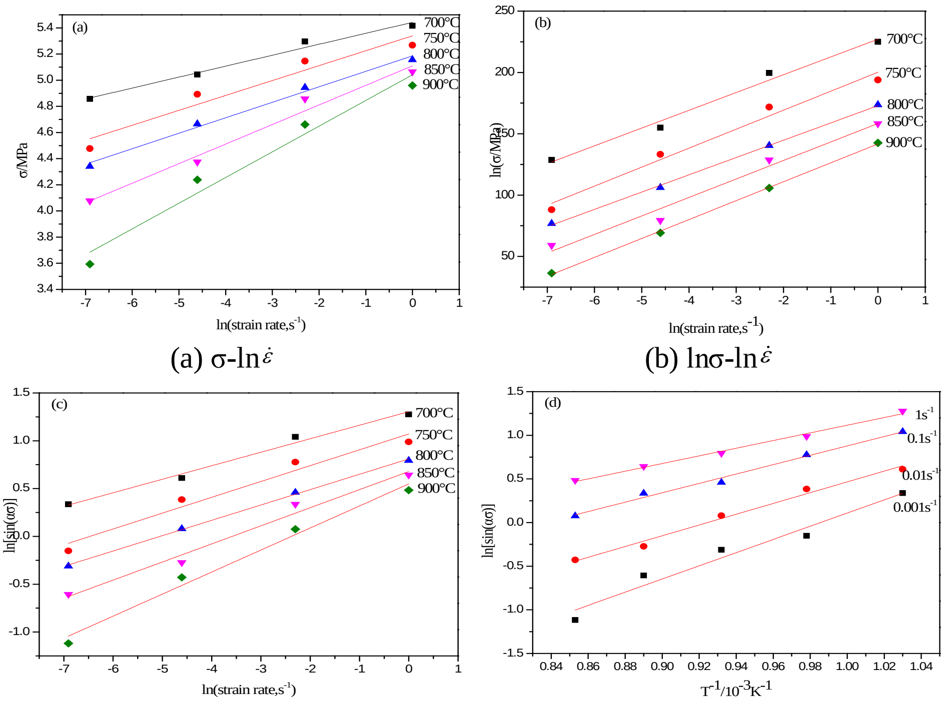
$$n_2 = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]} \tag{4}$$

$$k = \frac{\partial[\sinh(\alpha\sigma)]}{\partial(1/T)} = \frac{Q}{nR} \tag{5}$$

$$Q = n \cdot k \cdot R \tag{6}$$

When the deformation temperature T is constant, it can be obtained by combining the equation (6) and Figure 2(c), n=5.8. When the strain rate is constant, the linear relationship is obtained by the equation (5) in combination with figure 4(d), k=5938.699.When the strain reaches the peak value, the deformation activation energy Q=286.075kJ/mol, after optimization by Z-parameter, n_2=5.794 and the intercept $\ln A_3$=27.260 and the above constant is obtained. The Arrhenius constitutive equation of the TNTZ alloy at a strain of 0.3 is obtained by calculation:

$$\dot{\varepsilon} = \exp(27.26)[\sinh(8.841\times10^{-3}\sigma)]^n \exp(\frac{-286.075}{8.314T}) \tag{7}$$



(a) σ-ln$\dot{\varepsilon}$ (b) lnσ-ln$\dot{\varepsilon}$

(c) ln[sinh(ασ)]-ln$\dot{\varepsilon}$ (d) ln[sinh(ασ)]-1/T

Figure 2. Relationship between Flow Stress, Strain Rate and Deformation Temperature of TNTZ Alloy

The Z-parameter can be used to express the relationship between deformation temperature and strain rate of plastic deformation [7, 8] and the activation energy *Q* value is substituted, as shown in equation (8):

$$Z = \dot{\varepsilon}\exp(\frac{Q}{RT}) = \dot{\varepsilon}\exp(\frac{286.075}{RT}) \tag{8}$$

According to the equation of the hyperbolic sine function, the flow stress can be expressed as a function of the Z-parameter [9]:

$$\sigma = \frac{1}{\alpha}\ln\{(\frac{Z}{A})^{\frac{1}{n}} + [(\frac{Z}{A})^{\frac{2}{n}} + 1]^{\frac{1}{2}}\} \tag{9}$$

Substituting the experimental data into equation (9), the constitutive model of the peak stress, strain rate and temperature T represented by the Z-parameter is obtained as follows:

$$\sigma = \frac{1}{0.008841}\ln\{(\frac{Z}{6.9\times10^{11}})^{\frac{1}{5.794}} + [(\frac{Z}{6.9\times10^{11}})^{\frac{2}{5.794}} + 1]^{\frac{1}{2}}\} \tag{10}$$

3.3. Verifying the Constitutive Model

The experimental deformation temperature and strain rate were substituted into the above constitutive model to obtain a predicted value and compared with the experimental value. According to the prediction results, the mapping is performed for accuracy analysis and the model correlation coefficient R and the average relative error E are used to analyze the accuracy of the constitutive model. The expression is as follows:

$$R = \frac{\sum_{i}^{N}(C_i - \overline{C})(T_i - \overline{T})}{\sqrt{\sum_{i=1}^{N}(C_i - \overline{C})^2}\sqrt{\sum_{i=1}^{N}(T_i - \overline{T})^2}} \tag{11}$$

$$E = \frac{\sum_{i=1}^{N}\left|\frac{C_i - T_i}{C_i}\right| \times 100\%}{N} \tag{12}$$

Where C is the experimental value; T is the predicted value; N is the number of data points. according to equation (11) with (12), comparing the experimental values and experimental values, the results are shown in Figure 3. The correlation coefficient R of the values is 0.9714. The experimental value is basically consistent with the predicted value, that is, the constitutive model has higher precision.

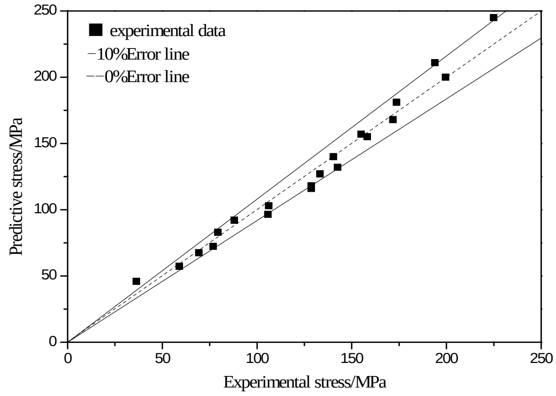


Figure 3. Flow Stress Results and Predicted Values of TNTZ Alloy

4. Discussion

The true stress-true strain of the TNTZ alloy decreases as the deformation temperature increases and the strain rate decreases. When the temperature is lower and the strain rate is higher, the curve shows a flow softening phenomenon; when the temperature is higher and the strain rate is lower, the curve shows a steady flow phenomenon.

Using the hyperbolic sinusoidal function to establish the stress-strain constitutive equation for TNTZ alloy, the activation energy is calculated to be 286.075kJ/mol and the constitutive equation as follow:

$$\sigma = \frac{1}{0.008841}\ln\{(\frac{Z}{6.9\times10^{11}})^{\frac{1}{5.794}} + [(\frac{Z}{6.9\times10^{11}})^{\frac{2}{5.794}} + 1]^{\frac{1}{2}}\}$$

Error analysis shows that the constitutive model has higher precision.

5. Acknowledgments

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6. References

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