Hot Compressive Behavior and Constitutive Equation of TC4-DT Alloy

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ABSTRACT

The effect of processing parameters on the hot deformation behavior of the α+β titanium alloy TC4-DT has been investigated by hot compressive testing on the Gleeble-1500 thermal simulation test machine in the temperature range of 908℃~1038℃, and at constant strain rate from 0.01s⁻¹ to 10s⁻¹. The results indicate that the hot deformation behavior of TC4-DT alloy is highly sensitive to the deformation temperature and strain rate. The flow behavior of the sample hot-deformed exhibits a peak stress followed by continuous flow softening in the α+β region, whereas in the β region, the true stress attains a steady state. The peak flow stress decreases with increasing the deformation temperature and decreasing the strain rate. According to the arrhenius equations, the constitutive equation of TC4-DT alloy is established, and the deformation activation energy are estimated to be about 694.508 KJ/mol in the α+β region and 252.496 KJ/mol in the β region, respectively.

INTRODUCTION

Due to their high strength, high toughness, low density, good corrosion resistance and fatigue properties, titanium alloys have been used widely in aerospace industries such as jet engines and airframe components[1-3]. TC4-DT is an α+β titanium alloy based on the chemical composition of TC4 (Ti-6Al-4V) with the extra low interstitial (ELI) grade with the contains of oxygen in the range of 0.09%~0.13%, which is to attain high fracture toughness and a good combination of strength, plastic and toughness. It is normally used at a medium tensile strength of 900MPa with good ductility, high fatigue and damage tolerance properties, which properties are equivalent to the Ti-6Al-4V ELI. According to its specific, TC4-DT alloy is particularly suitable to manufacture the integrated critical force-bearing component parts such as large frame, beam and joints in order to meet the high design damand for long life, security and dependability.

It is well known that many factors could influence the deformation behavior of titanium alloy during hot working, such as deformation temperature, strain rate and deformation degree[4,5]. The deformation processing window for titanium alloys is

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quite narrow as compared to aluminum alloys or steels. Furthermore, the evolution of microstructures is very sensitive to process parameters such as temperature, strain rate and strain[6]. Therefore, careful process control and profound knowledge of the influence of processing parameters on hot working behavior are important for the manufacture of titanium alloys components. The constitutive equation of materials can express the relationship among the hot working parameter of flow stress, strain rate and deformation temperature[7]. Therefore, a knowledge of the hot deformation behavior of TC4-DT alloy is very necessary to delineate the safe hot working condition and optimize the deformation processes, since it is helpful to avoid the expensive cost.

The objective of this work is to investigate the influence of process parameters on the flow stress behavior of TC4-DT alloy through isothermal compression at different hot working temperature and strain rates. Based on the compression test, the constitutive equation is constructed for TC4-DT alloy.

EXPERIMENTAL

Material. The material used in this work was triple melted by consumable vacuum arc remelting (VAR) process. The chemical composition in weight percent is 6.26Al, 4.18V, 0.03C, 0.03Fe, 0.012N, 0.004H, 0.11O, and the balance Ti. The β transus temperature is 988°C. The ingots was initially break down in β phase field around 1050°C followed by forging into plate in α+β field. The original microstructure of the plate is shown in Fig. 1.

![Figure 1. Initial microstructure of TC4-DT alloy.](image)

Compression Tests. The hot compression tests were carried out at the temperature from 908°C to 1038°C and at constant strain rate of 0.01, 0.1, 1 and 10s⁻¹ on the Gleeble-1500 simulator. The specimens were machined into cylindrical shape with 8mm in diameter and 12 mm in length along the plate axial direction. The thermocouples were welded in the middle surface of the specimens to measure and control the temperature during testing. The specimens were heated to the test temperature with a heating rate of 5°C, held for 5 minutes and then deformed at the selected temperature with a constant strain rate to a height reduction. In order to obtain the microstructure at high temperatures, the as-deformed specimens were immediately water quenched after compression tests. The load-stroke curves obtained from the compression tests are converted into true stress-strain curves by
standard equations. Proper lubricant of graphite pieces was used in order to reduce the effect of friction during the test.

**Microstructure Observation.** After tests, the hot compression specimens were cut into two parts as the metallographic specimens along the compression axial. The metallographic specimens were corroded using the solution containing 10% HNO₃, 20% HF and 70% H₂O. And the microstructure was observed using conventional optical microscopy.

**RESULTS AND DISCUSSION**

**Flow Behavior.** The typical true stress-true strain curves obtained of 908°C~1038°C and strain rates of 0.01s⁻¹~10s⁻¹ are presented in Fig. 2, which are representative of deformation behavior in three regions of α+β region, near β region and the β region, respectively. The curves show that the flow stress behavior of TC4-DT alloy is sensitive to compression temperature and strain rates. All the true stress-strain curves display a peak stress at the beginning of deformation, followed by a continuous flow softening till the end of hot compression to a true strain of 0.8. After the peak stress, the true stress decreased gradually with increasing the true strain, and then tended to a steady state. In general, flow stress was observed to decrease with the increase of compression temperature and to increase with increasing strain rate. Such continuous decrease in the flow stress with increasing strain has been previously reported for many titanium alloys[8-10].

As illustrated in Fig. 2, there is a significant difference in the true stress-true strain curves observed for deformation in the α+β region as compared to the β region. At the temperature below β transus, especially at 908°C, the true stress-true strain curves show an initial sharp peak, and then reach a steady-state stress condition at strain rate of 0.01s⁻¹ and 0.1s⁻¹ or decrease gradually at strain rate of 1s⁻¹ and 10s⁻¹. Consequently, when TC4-DT alloy is deformed in single β region, the true stress reaches a steady state or increase a little as deformation proceeds without showing a yield drop.
Figure 2. True stress-true strain curves of TC4-DT alloy deformed at the temperatures of (a) 908°C; (b) 968°C; (c) 998°C; (d) 1038°C, and the strain rates from 0.01s\(^{-1}\) to 10s\(^{-1}\).

It suggests that the strain hardening was greater than the dynamic recovery or dynamic recrystallization softening process, therefore the stress increased rapidly with the strain ascending in the early period of deformation. The flow stress would reach an initial sharp peak value, when hardening process was approximately equal to softening process. The phenomenon of initial sharp peak can be concluded that \(\alpha\) phase that acts as hard particles plays an important role in dislocation pinning. Therefore, the true stress increase abruptly due to a fast generation of dislocations in early state of deformation. However, when the becomes large enough, dislocation starts to slip from the pinning sites. Consequently, the true stress decrease sharply. Then, with the deformation continuing, the true stress almost remained constant[11].

When the deformation temperature at 908°C and 968°C, the strain hardening was a little higher than the dynamic recovery or dynamic recrystallization softening process at high strain rate of 10s\(^{-1}\).

Figure 3. Variation of peak flow stress with temperature at different strain rate from 0.01s\(^{-1}\) to 10s\(^{-1}\).

In addition, the peak flow stress with temperature at different strain rate is shown Fig. 3. It is shown that the larger the strain rate is, the larger the peak stress is, especially at high strain rate of 10s\(^{-1}\). The peak stress value decreased with the increase of deformation temperature. When the temperature increases over 998°C, the decrease of the flow stress becomes slow. There may be several suggests to consider this reasons[12, 13]. This is mainly due to the increase of strain rates, the dynamic recovery or dynamic recrystallization could not supply in time and in sufficient, consequently the stress increases with increasing the strain rates.

**Constitutive Equation and Activation Energy.** Further analysis of the deformation temperature and strain rate dependency on flow stress is required for understanding the mechanisms of hot deformation. The high temperature
deformation of metal is a thermal activation process, which is affected by the deformation temperature, strain rate and other factors. It is well known that the material flow stress model can be expressed as a function of stress, strain rate and temperature, and the relationship of temperature and strain rate can be also denoted by a parameter $Z$:

$$\sigma = \sigma(Z, \dot{\varepsilon}) \quad (1)$$

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \quad (2)$$

Where $\sigma$ is the flow stress, $\dot{\varepsilon}$ is the strain rate, $Q$ is the average apparent activation energy of deformation, $R$ is the ideal gas constant ($8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), $T$ is the temperature in Kelvin, $n$ is the stress exponent, and $Z$ is a Zener-Hollomon parameter[6], whose physical meaning is the temperature compensated strain rate.

For the relationship between the flow stress and the strain rate, there are three expression of Arrhenius constitutive models that have been widely reported in literatures to model the material flow behavior as the following[14]:

$$\dot{\varepsilon} = A_1 \sigma^n \exp\left(-\frac{Q}{RT}\right) \quad (3)$$

$$\dot{\varepsilon} = A_2 \exp(\beta \sigma) \exp\left(-\frac{Q}{RT}\right) \quad (4)$$

$$\dot{\varepsilon} = A[\sinh(\alpha \sigma^n)] \exp\left(-\frac{Q}{RT}\right) \quad (5)$$

where $A_1, A_2, A, n_1, n, \beta$, and $\alpha$ are material constants. The relationship among $\alpha$, $\beta$ and $n_1$ is

$$\alpha = \beta / n_1 \quad (6)$$

The power law, Eqn. (3) and the exponential law, Eqn. (4), are suitable for a low stress and a high stress, respectively. The law of Eqn. (5) is generally used to describe the flow stress and deformation behavior over a wide range of temperature and strain rate.

By taking natural logarithm, Eqn. (3) and Eqn. (4) can be written as follows:

$$\ln \sigma = \frac{\ln \dot{\varepsilon}}{n_1} - \frac{\ln A_1}{n_1} \quad (7)$$

$$\sigma = \frac{\ln \dot{\varepsilon}}{\beta} - \frac{\ln A_2}{\beta} \quad (8)$$

Because of that the material constants of $A_1, A_2, Q, R$, and $T$ is invariable, Taking derivative for Eqn. (7) and Eqn. (8) yields

$$n_1 = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma} \quad (9)$$
\[ \beta = \frac{\partial \ln \dot{\varepsilon}}{\partial \sigma} \]  

(10)

The relation of \( \ln \sigma - \ln \dot{\varepsilon} \) when the stress is low is shown in Fig. 4 (a), and the relation of \( \sigma - \ln \dot{\varepsilon} \) when the stress is high is shown in Fig. 4 (b). Since the transus temperature of TC4-DT alloy is about 986°C, the kinetic parameters may be evaluated separately into the two-phase region (908-968°C) and the signal-phase region (998-1038°C). By linear regression of the relations of \( \ln \sigma - \ln \dot{\varepsilon} \) and \( \sigma - \ln \dot{\varepsilon} \) at different temperature, the values of \( n_1 \) and \( \beta \) are obtained for the \( \alpha+\beta \) region and the \( \beta \) region. Then taking the values into Eqn. (6), the value of \( \alpha \) in the \( \alpha+\beta \) region and the \( \beta \) region can be inferred to be 0.0117 and 0.0205, respectively.

If the activation energy \( (Q) \) does not change with deformation temperature \( (T) \), the Eqn. (5) takes into logarithm forms as

\[ \ln \dot{\varepsilon} = \ln A + n \ln \left[ \sinh(\alpha \sigma) \right] - Q/RT \]  

(11)

Taking partial derivative for Eqn. (11), \( n \) and \( Q \) can be obtained as follows:

\[ n = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \left[ \sinh(\alpha \sigma) \right]} \bigg|_T \]  

(12)

\[ Q = Rn \frac{\partial \ln \left[ \sinh(\alpha \sigma) \right]}{\partial \left( 1000/T \right)} \bigg|_\varepsilon = R \frac{\partial \ln \dot{\varepsilon}}{\partial \ln \left[ \sinh(\alpha \sigma) \right]} \bigg|_T \frac{\partial \ln \left[ \sinh(\alpha \sigma) \right]}{\partial \left( 1000/T \right)} \bigg|_\varepsilon \]  

(13)

According to the value of \( \alpha \) and the true stress-true strain curves, the stress exponent \( n \) and the activation energy \( Q \) for deformation is calculated in the \( \alpha+\beta \) region and the \( \beta \) region. The plot of \( \ln \dot{\varepsilon} \) versus \( \left[ \sinh(\alpha \sigma) \right] \) and the plot of \( \ln \left[ \sinh(\alpha \sigma) \right] \) versus \( T^{-1} \) in both phase fields are shown in Fig. 5. It can be seen that the slope of the fitted line in Fig. 5(b) is changing which indicates different deformation mechanism. By regression analyzing the curves shown in Fig. 5, the values of the stress exponent \( n \) and the activation energy \( Q \) of TC4-DT alloy is determined to be 3.185, 694 kJ/mol in the \( \alpha+\beta \) region and 4.148, 252 kJ/mol in the \( \beta \) region, respectively.
The constitutive equation that describes the flow behavior as a function of the strain rate and deformation temperature for TC4-DT alloy may be written as

\[ \dot{\varepsilon} = e^{65.69} \left[ \sinh(0.00117 \sigma) \right]^{3.185} \exp\left(-6.94 \times 10^5 / RT\right) \]  

for the \(\alpha+\beta\) region, and

\[ \dot{\varepsilon} = e^{23.155} \left[ \sinh(0.0205 \sigma) \right]^{4.148} \exp\left(-2.52 \times 10^5 / RT\right) \]  

for the \(\beta\) region, respectively.

![Figure 5](image)

Figure 5 Plots of (a) \(\ln \dot{\varepsilon} - \ln[\sinh(\alpha\sigma)]\) and (b) \(\ln[\sinh(\alpha\sigma)] - T^{-1}\).

Substitution of Eqn. (5) into Eqn. (2) yields

\[ Z = A \ln[\sinh(\alpha\sigma)]^n \]  

(16)

Take the natural logarithm of each side, then

\[ \ln Z = \ln A + n \ln[\sinh(\alpha\sigma)] \]  

(17)

The effects of strain rate and temperature on the deformation behaviors can be represented by the linear relationship of \(\ln Z\) versus \(\ln[\sinh(\alpha\sigma)]\), and the plot of \(\ln Z\) versus \(\ln[\sinh(\alpha\sigma)]\) is shown in Fig. 6 with a correlation coefficient (R) of 0.984 and 0.991 in the \(\alpha+\beta\) region and the \(\beta\) region, respectively. The high values of \(R\)-squared exhibit a good prediction capability of hyperbolic sine function for the experimental data in the tested strain rates and temperatures.
SUMMARY

The hot deformation behaviors of TC4-DT alloy are investigated by isothermal compression tests in the temperature from 908°C to 1038°C and strain rate from 0.01s⁻¹ to 10s⁻¹. Based on the analysis of flow stress data, constitutive equation is developed for TC4-DT alloy in this work. The following principal conclusions can be drawn from the present study:

(1) The flow behavior of TC4-DT alloy is sensitive to the strain rate and the compression temperature. The peak Flow stress decrease with increasing of compression temperature and decreasing of strain rate.

(2) According to the data of the hot compression tests, the values of activation energy $Q$ of TC4-DT alloy is determined to be 694 kJ/mol in the α+β phase field and 252 kJ/mol in the β phase field, respectively.

(3) The constitutive equation for TC4-DT alloy is

$$
\dot{\varepsilon} = e^{65.698 \sinh(0.00117\sigma)} \exp(-6.94 \times 10^4 / RT)
$$

and

$$
\dot{\varepsilon} = e^{23.155 \sinh(0.0205\sigma)} \exp(-2.52 \times 10^2 / RT)
$$

in the α+β phase field and in the β phase field, respectively. The high values of $R$-squared exhibit a good predication capability of hyperbolic sine function for the experimental data in the tested temperatures and strain rates.

REFERENCES


