

Study on Thermal Deformation Behavior of TC4 – ELI Titanium Alloy

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Abstract. The TC4-ELI titanium alloy was subjected to the hot compression deformation test by the Gleeble-1500D thermal simulation test machine. The thermal deformation behavior of the TC4-ELI titanium alloy was studied under the condition of 850°C-1050°C, 0.001s⁻¹-10s⁻¹ strain rate and 50% deformation; The constitutive equation of TC4-ELI titanium alloy was established based on the hyperbolic sine model of Arrhenius equation. The results show that the flow stress of TC4-ELI titanium alloy decreases with the increase of temperature at high temperature. The calculated heat activation energy of TC4-ELI titanium alloy is 300367.5807J / mol.

1. Introduction

Titanium alloy with high strength, low density, high melting point and good corrosion resistance, is widely used in aviation, aerospace, ship and other fields[1,2]. TC4-ELI titanium alloy has good strength, shaping, heat resistance, corrosion resistance, and it is so widely used that amounts for 75% -85% of the total amount of titanium alloy[3]. TC4-ELI titanium alloy has large deformation resistance, is difficult to process at room temperature, and is sensitive to thermal processing parameters, so it is difficult to formulate the process in forming process. The oxidation resistance of TC4-ELI titanium alloy is poor at high temperature, which limits its application to some extent [4-8]. Therefore, the thermal deformation behavior of TC4-ELI titanium alloy is urgently needed to research.

2. Materials and methods

The chemical composition of TC4-ELI titanium alloy is shown in table 1. The heat treatment process is that the material is heated to 950°C and kept 65 minutes, then is air-cooled to room temperature.



The specimens were processed into $\Phi 8 \text{ mm} \times 12 \text{ mm}$ cylinders and the two ends of the cylinders were polished with fine sandpaper. The compression test was carried out on a Gleeble-1500D thermal simulator. According to the TC4-ELI titanium alloy transformation point temperature, the hot pressing temperature is selected as 850°C , 900°C , 950°C , 1000°C , 1050°C , the strain rate is 0.001s^{-1} , 0.01s^{-1} , 0.1s^{-1} , 1s^{-1} , 10s^{-1} and total compression deformation is 50%. In order to reduce the friction force, the graphite sheet is added between the test machine indenter and the end of the cylindrical specimen before the test. At the beginning of the test, the specimen was heated to 1100°C at a rate of 10°C/s and held 5 min, then was cooled to each deformation temperature at a rate of 5°C/s and held 10 seconds to heat evenly. Finally, the specimens were compressed to 50% of the total deformation at specified strain rates. After the completeness of compression process, the specimens were subjected to water quenching to preserve the high temperature deformation. The hot compression test curve is shown in figure 1.

Table.1 The mass fraction of each element of TC4-ELI titanium alloy

element	Al	V	Fe	O	C	N	H
wt%	5.92	3.91	0.188	0.092	0.0081	0.008	0.004

3.Results and analysis

3.1.True stress-strain curves of TC4 - ELI titanium alloy

The true stress-strain curves of TC4-ELI titanium alloy at different temperatures are shown in figure1. With the increasing strain rate, the stress of the TC4-ELI titanium alloy increases rapidly to a peak stress and then the stress tends to be stable. The peak stress increases with the increase of strain rate, and decreases with the increase of hot compression temperature. In the initial stage of deformation, a significant work hardening phenomenon that the stress increases sharply is mainly due to the resistance of the dislocation motion increases with the increase of the dislocation density. When the peak stress is reached, the stress enters the steady state or falls a little and then into the steady state (strain rates 0.001 s^{-1} and 10 s^{-1}), showing typical dynamic recovery characteristics on the stress-strain curve. The main reason is that hardening and dynamic softening achieve a relative balance.

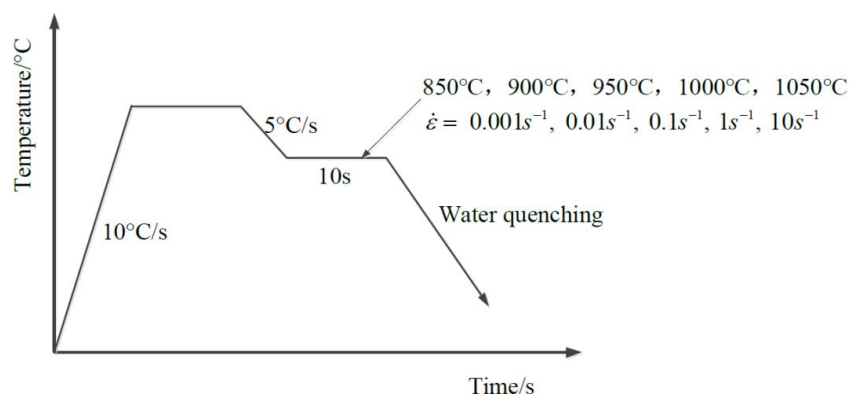
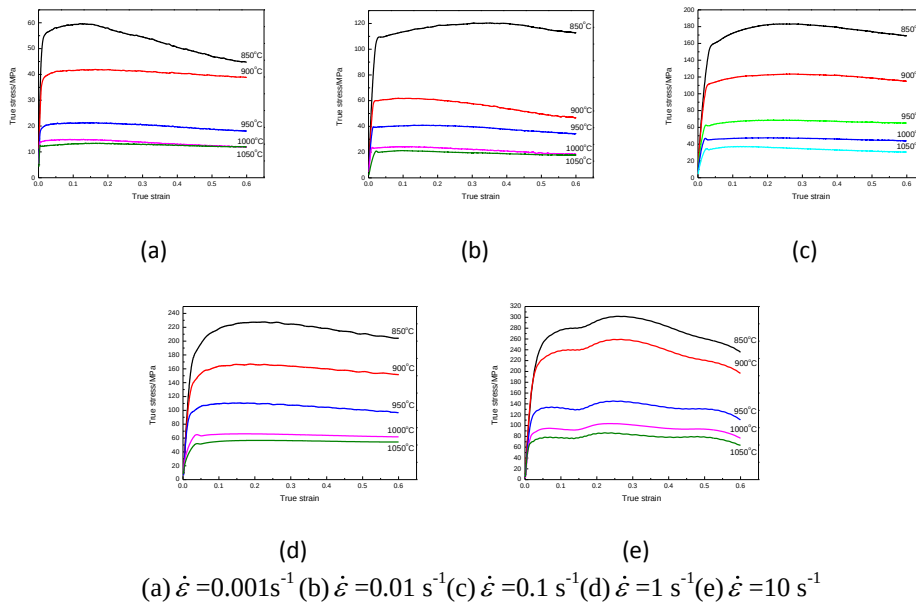


Figure1. The curve of thermal compression

As shown in figure 2, when the hot compression of TC4-ELI titanium alloy is occurred, the

stress peak shifts to the right and decreases with the increase of the deformation temperature under the same strain rate, which indicates that the decrease of deformation resistance of TC4-ELI titanium alloy with the increase of temperature and the dynamic recrystallization at this time. At the same deformation temperature, the higher the strain rate, the higher the peak value of the stress, the greater the corresponding strain. The greater the strain rate, the shorter the corresponding deformation time. The time of dislocation movement significantly reduces, which is not conducive to dynamic response and dynamic recrystallization.



(a) $\dot{\epsilon} = 0.001 \text{ s}^{-1}$ (b) $\dot{\epsilon} = 0.01 \text{ s}^{-1}$ (c) $\dot{\epsilon} = 0.1 \text{ s}^{-1}$ (d) $\dot{\epsilon} = 1 \text{ s}^{-1}$ (e) $\dot{\epsilon} = 10 \text{ s}^{-1}$
Figure 2. True stress-true strain curves of TC4-ELI titanium alloy under different strain rates and temperatures

3.2. Constitutive model of TC4-ELI titanium alloy

The constitutive model of TC4-ELI titanium alloy uses a hyperbolic sine model with the Arrhenius equation, including strain rate, deformation heat activation energy Q , deformation temperature T and molar gas constant R , to describe the relations between strain rate, stress, deformation temperature, etc. As shown in equation (1):

$$\dot{\epsilon} = A F(\sigma) \exp[-Q/RT] \quad (1)$$

Equation (2) is the formula for the different stress levels in the hyperbolic sine model of the Arrhenius equation.

$$\begin{cases} F(\sigma) = \sigma^{n_1} & (\alpha\sigma < 0.8) & (a) \\ F(\sigma) = \exp(\beta\sigma) & (\alpha\sigma > 1.2) & (b) \\ F(\sigma) = [\sinh(\alpha\sigma)]^n & (\text{for all stress}) & (c) \end{cases} \quad (2)$$

In equation (1) and (2): $\dot{\epsilon}$ is the strain rate (s^{-1}); σ is flow stress (MPa); Q is the activation of the activation energy (kJ/mol); T is the deformation temperature; R is the molar gas

constant; A, n, α and β are the material constant, $\alpha = \beta / n_1$.

The (a) and (b) of equation (2) are respectively taken into the equation (1), then the logarithm of both sides can be obtained at the same time:

$$\ln \dot{\epsilon} = \ln A_1 + n_1 \ln \sigma - Q / RT \quad (3)$$

$$\ln \dot{\epsilon} = \ln A_2 + \beta \sigma - Q / RT \quad (4)$$

By the equation (3) and (4), when the temperature is constant, $\ln \dot{\epsilon} - \ln \sigma$, $\ln \dot{\epsilon} - \sigma$ both have a linear relationship. $\ln \dot{\epsilon} - \ln \sigma$ and $\ln \dot{\epsilon} - \sigma$ were drawn from the experimental data, the linear relationship between the two is fitted by the least squares method. As shown in figure 3 (a), (b). From the equation (3) and (4), n_1 and β are slopes of $\ln \dot{\epsilon} - \ln \sigma$ and $\ln \dot{\epsilon} - \sigma$ respectively. The average value of n_1 is 5.083 and the average of β is 0.085 and the stress level parameter $\alpha = 0.017 \text{ mm}^2 \cdot \text{N}^{-1}$ can be obtained by $\alpha = \beta / n_1 \text{ mm}^2 \cdot \text{N}^{-1}$.

The (c) of the equation (2) is taken into equation (1), then the logarithm of both sides can be obtained at the same time:

$$\ln \dot{\epsilon} = \ln A + n \ln [\sinh(\alpha \sigma)] - Q / (RT) \quad (5)$$

When the deformation temperature is constant, equation (6) is the result of partial derivative of $1/T$ in equation (5). Drawing the $\ln \dot{\epsilon} - \ln [\sinh(\alpha \sigma)]$ relationship diagram and using the least squares method to fit out the curve, the slope of the average value is the value of n , as shown in figure 3 (c). Finally, the material flow stress index $n = 5.028$.

$$\frac{\partial \ln \dot{\epsilon}}{\partial (1/T)} = n \frac{\partial \ln [\sinh(\alpha \sigma)]}{\partial (1/T)} \quad (6)$$

When the strain rate is constant, equation (7) is the result of partial derivative of $1/T$ in equation (6). Drawing the $\ln [\sinh(\alpha \sigma)] - 1/T$ relationship diagram and using the least squares method to fit out the curve, as shown in figure 2 (d), coefficient $s = 7188.806$.

$$\frac{Q}{Rn} = \left\{ \frac{\partial \ln [\sinh(\alpha \sigma)]}{\partial (1/T)} \right\}_{\dot{\epsilon}} \quad (7)$$

Equation (9) can be obtained by equation (6) and (7), the thermal activation energy of the deformation is $Q = 300367.5807 \text{ J / mol}$.

$$Q = R \left\{ \frac{\partial \ln \dot{\epsilon}}{\partial \ln [\sinh(\alpha \sigma)]} \right\}_T \cdot \left\{ \frac{\partial \ln [\sinh(\alpha \sigma)]}{\partial (1/T)} \right\}_{\dot{\epsilon}} \quad (8)$$

The strain rate factor Zener-Hollomon parameter Z is used to describe the effect of strain rate and heat distortion temperature T on deformation.

$$Z = \dot{\epsilon} \exp[Q / RT] \quad (9)$$

Z can be obtained by the equation (1) and (9):

$$Z = A [\sinh(\alpha \sigma)]^n \quad (10)$$

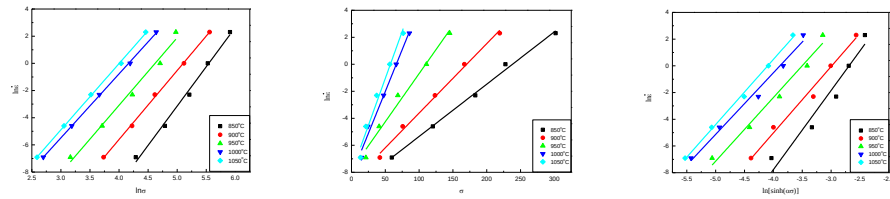
The logarithm of the equation (10) is taken on both sides simultaneously, the equation (11):

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

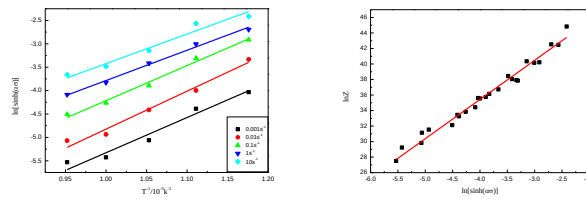
By equation (11), $\ln A$ is the intercept of $\ln Z - \ln [\sinh(\alpha \sigma)]$. The thermal deformation temperature T , strain rate $\dot{\epsilon}$ and thermal activation energy Q were taken into equation (11) to calculate Z under various thermal deformation conditions. The relation of $\ln Z - \ln [\sinh(\alpha \sigma)]$ is analyzed by the linear regression, as shown in figure 3, $\ln A = 55.63916$ is found, and the structure factor of the material is $A = 1.458 \times 10^{24} \text{ s}^{-1}$.

From the above analysis and calculation, under the strain rate $0.001\text{s}^{-1} - 10\text{s}^{-1}$ and the thermal deformation temperature of $850^{\circ}\text{C} - 1050^{\circ}\text{C}$, the constitutive equation of the flow stress can be expressed as follows:

$$\dot{\varepsilon} = 1.458 \times 10^{24} [\sinh(0.017\sigma)]^{5.028} \exp\left(-\frac{300367.5807}{RT}\right) \quad (12)$$



(a) $\ln \dot{\varepsilon} - \ln \sigma$ (b) $\ln \dot{\varepsilon} - \sigma$ (c) $\ln \dot{\varepsilon} - \ln \sinh(\alpha\sigma)$



(d) $\ln [\sinh(\alpha\sigma)] - 1/T$ (e) $\ln Z - \ln [\sinh(\alpha\sigma)]$

(a) $\ln \dot{\varepsilon} - \ln \sigma$ (b) $\ln \dot{\varepsilon} - \sigma$ (c) $\ln \dot{\varepsilon} - \ln \sinh(\alpha\sigma)$ (d) $\ln [\sinh(\alpha\sigma)] - 1/T$ (e)

$$\ln Z - \ln [\sinh(\alpha\sigma)]$$

Figure 3. The analysis figures of constitutive equation

4. Conclusion

- 1) With the increasing strain rate, the stress of the TC4-ELI titanium alloy increases rapidly to a peak stress and then the stress tends to be stable. The stress peak is shifted to the right and decreases with the increase of the deformation temperature under the same strain rate. The peak stress increases with the increase of strain rate under the same deformation temperature.
- 2) The thermal deformation activation energy of TC4-ELI titanium alloy was calculated to be 300367.5807 J/mol, and the hyperbolic sine constitutive equation with Z parameters was constructed: It provides reference for future production and finite element simulation analysis.

$$\dot{\varepsilon} = 1.458 \times 10^{24} [\sinh(0.017\sigma)]^{5.028} \exp\left(-\frac{300367.5807}{RT}\right)$$

Acknowledgments

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