Characterization of hot deformation behavior of TC32 titanium alloy

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Abstract. The hot deformation behavior of TC32 alloy is investigated in the temperature range of 873~948℃ and strain rate range of 0.01, 0.1, 1, and 10 s⁻¹ by hot compression experiments, and the constitutive relationship of TC32 alloy is established on the base of the Arrhenius equations. It is found that, with an increase in deformation temperature and the strain rate reduction, the flow stress decreases, and the deformation mechanisms of TC32 alloy exhibit dynamic recovery feature within the high-temperature region and recrystallization feature within the low-temperature one. Deformation activation energy values are 404.7 kJ/mol in the alpha-beta region and 526.6 kJ/mol in the beta region. Finally, the constitutive equation of TC32 titanium was established.

1. Introduction

With the rapid development of the new generation of the aeronautic and astronomic vehicle, tank and switch antitank vehicle, etc. the design and application demand for excellent performance, high weight loss, long-lived and low-cost increase [1, 2]. The innovative TC32 titanium alloy was developed by alloying, comprehensive strengthening and toughening technologies in Beijing Institute of Aeronautical Materials. The alloy is a new kind of Ti-Al-Mo-Cr-Zr system titanium alloy with low cost and excellent performance of low density, good strength-plastic-toughness-fatigue properties which could match different microstructure types [3-7].

The mechanical behavior in thermal deformation is related to chemical composition, microstructure and deformation temperature, deformation degree, strain rate of the alloy, etc. [8-12]. High temperature working above the beta transus (beta phase field) is an essential step for homogenization of the cast structure while deformation below the transus (alpha-beta phase field) converts the transformed beta structure to equiaxed alpha-beta structure [13].

2. Experimental procedures

The TC32 (Ti-5Al-3Mo-3Cr-IZr-0.15Si) titanium alloy which was three-time melted by vacuum self-consuming arc melting, forged in the alpha-beta region and duplex-annealed in the investigation. A bimodal microstructure containing 40% primary alpha phase was obtained, which is characterized that discontinuous primary alpha phase equiaxed or elliptical-shaped were distributed in the transfer beta matrix with lamellar microstructure, as depicted in figure 1. And the mechanical properties of the original condition of TC32 alloy are shown in table 1. The phase transition temperature measured was 918℃. Cylindrical specimens of TC32 alloy machined to Φ (8±0.5) mm × (15±0.1) mm were prepared. The hot compression tests were carried out on the Gleeble 3500 thermal simulation testing machine. The specimens were heated to the testing temperature for 5 mins with the heating rate of 10℃/min,
then deformed. The as-deformed samples were immediately quenched in water for retaining high temperature structure. The temperature of 873, 888, 903, 933, and 948°C and strain rates of 0.01, 0.1, 1, and 10s\(^{-1}\) were carried out in the experiments, the true stress-strain curves were obtained according to data collected automatically by a Gleeble 3500 thermal simulation machine, including load, displacement, temperature, and time, etc. The stress-strain curves in different conditions were analyzed, and the constitutive equation was established.

![Figure 1. The original microstructure of TC32 titanium alloy](image)

**Table 1.** Mechanical properties of the original condition of TC32 alloy at room temperature.

| Mechanical properties | \(\sigma_b\) (MPa) | \(\sigma_{0.2}\) (MPa) | \(\delta_{0.5}\) (%) | \(\Psi\) (%) | \(\alpha_k\) (J·cm\(^{-2}\)) | \(K_{IC}\) (MPa·m\(^{1/2}\)) |
|-----------------------|-----------------|-----------------|-----------------|-----------|-----------------|-----------------|
| Tensile properties    | 1021            | 960             | 15.9            | 52.6      | /               | /               |
| Impact properties     | /               | /               | /               | /         | 98.9            | /               |
| Fracture toughness    | /               | /               | /               | /         | /               | 119             |

3. Results and Discussion

3.1. *True stress-true strain curves*

The true stress-true strain curves obtained at different deformation temperature are shown in figure 2, the hot deformation behavior of TC32 titanium alloy is sensitive with temperature and strain rate. The stress decline with increasing temperature and decreasing strain rate. The curves exhibit an obvious peak which is attributed to dynamic recrystallization at the beginning of hot deformation, dynamic recovery and working-hardening occur concomitantly, the dislocation density increase until a critical value, new grains nucleate and lead to flow-softening. A balance is established, and the phenomenon presents a stable level in the curves with a slight fluctuation because of work-hardening and flow-softening processing alternately in the steady-state stage, especially at a higher temperature.

The peak flow stress \(\sigma_p\) of TC32 titanium alloy with different conditions of strain rate and temperature are listed in table 2. It can be found that when temperature increases, the peak flow stress decrease especially under a higher strain rate of 10s\(^{-1}\), \(\sigma_p\) have little change when 0.1s\(^{-1}\). At high strain amplitude, dislocation multiplication occurred, and plastic deformation cannot be fully completed. As a result, the degree of elastic deformation increase and lead to the rise in the peak of flow stress. Strain rate has a significant impact on the properties of titanium alloy; the larger strain rate makes a more considerable deformation resistance and higher energy loss. On the contrary, higher energy loss caused by longer deformation time makes a failure of hot deformation.
Figure 2. Flow curves obtained under different strain rate: (a) 0.1s$^{-1}$ and (b) 1s$^{-1}$.

Table 2. Measured values of the peak flow stress ($\sigma_p$/MPa) of titanium alloy with different conditions of strain rate and temperature.

| Strain rate(s$^{-1}$) | Temperature (°C) | 873 | 888 | 903 | 933 | 948 |
|----------------------|------------------|-----|-----|-----|-----|-----|
| 0.01                 |                  | 81  | 71  | 65  | 58  | 56  |
| 0.1                  |                  | 145 | 132 | 115 | 111 | 92  |
| 1                    |                  | 211 | 199 | 182 | 157 | 143 |
| 10                   |                  | 305 | 285 | 249 | 215 | 190 |

3.2. Kinetic analysis

The flow stress depends on temperature and strain rate during the high temperature deformation. To understand the rate-controlling step during the deformation, the flow stress data are analyzed using the kinetic rate equation given by:

$$ \sigma = \sigma(Z, \epsilon) $$

$$ Z = \dot{\epsilon} \exp \left[ \frac{Q}{R T} \right] $$

where $\dot{\epsilon}$ is strain rate, $\sigma$ is flow stress, $E$ is elastic modulus, $Q$ is apparent activation energy, $R$ is ideal gas constant, $T$ is the temperature in Kelvin, and $Z$ is the Zener-Hollomon parameter.

The deformation mechanism of titanium alloy is related to strain rate. The relationship between flow stress and strain rate is described by the equation reported in [14-16] as follows:

$$ \dot{\epsilon} = A_1 \sigma^{n_1} \exp \left[ -\frac{Q}{R T} \right] $$

$$ \dot{\epsilon} = A_2 \exp(\beta \sigma) \exp \left[ -\frac{Q}{R T} \right] $$

$$ \dot{\epsilon} = A [\sin(\alpha \sigma)]^{n} \exp \left[ -\frac{Q}{R T} \right] $$

where $A_1, A_2, A, n_1, n, \beta, \alpha$ are frequency factors, and $\alpha = \beta/n_1$. Equations (3-5) are generally used to describe the low-, high-stress, and entire stress regions, respectively. The natural logarithm of equation (3-4) can be obtained as equations (6) and (7):

$$ \ln \dot{\epsilon} = \ln A_1 + n_1 \ln \sigma - \frac{Q}{R T} $$

$$ \ln \dot{\epsilon} = \ln A_2 + \beta \sigma - \frac{Q}{R T} $$

Taking partial derivative for equations (8) and (9), the values of $n_1$ and $\beta$ can be obtained as follows:

$$ n_1 = \frac{\partial \ln \dot{\epsilon}}{\partial \ln \sigma} $$

$$ \beta = \frac{\partial \ln \dot{\epsilon}}{\partial \sigma} $$
\[ \beta = \frac{\partial \ln \dot{\varepsilon}}{\partial \sigma} \]  

(7)  

A plot of \( \ln \dot{\varepsilon} \) vs. \( \sigma \) is shown in figure 3, while \( \ln \dot{\varepsilon} \) vs. \( \ln \sigma \) is depicted in figure 4, while \( n_1 \) and \( \beta \) have been estimated of 5.1877 and 0.0391, respectively, then \( \alpha \) is obtained by calculation of 0.00753.

Figure 3. The interaction between \( \ln \dot{\varepsilon} \) and \( \ln \sigma \)

Figure 4. The interaction between \( \ln \dot{\varepsilon} \) and \( \sigma \)

The natural logarithm of equation (5) can be obtained as:

\[ \ln \dot{\varepsilon} = \ln A + n \ln[\sinh(\alpha \sigma)] - Q(RT)^{-1} \]  

(10)  

Then the value of \( n_2 \) can be obtained as:

\[ n = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha \sigma)]} \]  

(11)  

The hot deformation activation energy \( Q \) (J/mol) can be calculated by the following equation [14]:

\[ Q = R \frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha \sigma)]} \bigg|_{T} \frac{\partial \ln[\sinh(\alpha \sigma)]}{\partial (1000T^{-1})} \bigg|_{T} = Rn_2n_3 \]  

(12)

A plot of \( \ln \dot{\varepsilon} \) vs. \( \ln[\sinh(\alpha \sigma)] \) is given in figure 5, \( \ln[\sinh(\alpha \sigma)] \) vs. \( 1000T^{-1} \) in figure 6, \( n_2 \) and \( n_3 \) have been estimated of 3.55327/4.32130 and 13.6976/14.6564 in alpha-beta region/beta region, respectively.

Figure 5. The interaction between \( \ln \dot{\varepsilon} \) and \( \ln[\sinh(\alpha \sigma)] \)

Figure 6. Interaction between \( \ln[\sinh(\alpha \sigma)] \) and \( 1000T^{-1} \)

According to equation (11), the hot deformation activation energy \( Q \) can be calculated of 404.7kJ/mol and 526.6kJ/mol in the alpha-beta region and beta region respectively.

Substitution of equation (5) into equation (2) yields

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

(13)  

Take the natural logarithm for equation (14) is obtained as follows:
\[ \ln Z = \ln A + n \ln [\sinh(\alpha \sigma)] \]  \hspace{1cm} (14)

A plot of \( \ln Z \) vs. \( \ln [\sinh(\alpha \sigma)] \) is depicted in figure 7. It yields that the value of \( n \) is 3.54235/4.30593 and \( \ln A \) is 39.26174/50.51993 in alpha-beta region/beta region. Taking \( A, \alpha, n, Q \) which are obtained from the above calculation into equation (5) and the constitutive equation for TC32 titanium alloy can be expressed as equations (15) and (16).

In the alpha-beta region:
\[ \dot{\varepsilon} = \left[ \sinh(0.00753 \sigma) \right]^{3.54235} \exp\left[ -404700(RT)^{-1} + 39.26174 \right] \]  \hspace{1cm} (15)

In the beta region:
\[ \dot{\varepsilon} = \left[ \sinh(0.00753 \sigma) \right]^{4.30593} \exp\left[ -526600(RT)^{-1} + 50.51993 \right] \]  \hspace{1cm} (16)

![Figure 7. Interaction between lnZ and ln[sinh(ασ)].](image)

4. Conclusions
In this study, high-temperature deformation tests with different temperatures of 873~943°C and strain rate of 0.01~10s\(^{-1}\) were carried out. The conclusions obtained from the experimental results are as follows:

(1) With an increase in temperature and decrease in strain rate, the reduction of flow stress will occur.

(2) The deformation activation energy of TC32 alloy is 404.7kJ/mol and 526.6kJ/mol in the alpha-beta and beta regions, respectively. The constitutive equations were obtained.

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References
[1] Zhu Z S 2014 J Aeronaut Mater 34 44-50
[2] Brewer D.W.D, Brid R.K and Wallace T A 1998 Mater. Sci. Eng. A. 243 299-304
[3] Fei Y, Zhu Z S, Wang X N, Li J, Shang G Q and Zhu L W 2013 Rare metals 37 186-91
[4] Wang X N, Fei Y, Liu Z, Shang G Q, Li J, Zhu L W and Zhu Z S 2013 Titanium 30 7-10
[5] Shang G Q, Wang X N, Fei Y, Li J, Zhu L W and Zhu Z S 2013 Failure analysis and Prevention. 8 74-78
[6] Li M B, Zhu Z S, Wang X N, Fei Y, Zhu L W, Shang G Q and Li J. 2016 J Aeronaut Mater. 36 7-13
[7] Zhu Z S, Shang G Q, Wang X N, Fei Y and Li J 2012 Titanium 29 1-5
[8] Li J, Zhu L W, Wang X N, Fei Y, Shang G Q and Zhu Z S 2016 Mater Sci Forum 849 332-39
[9] Yao P P, Li P, Li C M, Xue K M and Gün G Q 2015 Rare metals 11 967-74
[10] Cui X F, Mi X J, Luo Z, Tao H M and Lin C G 2015 JMEP 24 67-79
[11] Mao B P, Guo S L and Shen J 2008 Rare Metals 32 674-78
[12] Tang Z, Yang H, Sun Z C, Li Z Y and Duan H 2008 Chin J Nonferrous Met 18 722-27.
[13] Seshacharyulu T, Medeiros S C, Morgan J T, Malas J C, Frazier W G and Prasad Y V 1999 Scripta Mater 3 283-88
[14] Zhu L W, Wang X N, Fei Y, Li J and Zhu Z S 2016 Mater Sci Forum 849 309-16.
[15] Feng L, Qu H L, Zhao Y Q, Li H, Zhang Y N and Zeng W D 2004 J Aeronaut Mater 24 11-13
[16] Liu Q, Xue X Y, Fu B Q and Wang Y C 2009 Mater Heat Treat. 38 43-47