Establishment of Thermal Deformation Constitutive Equation of TA15 Titanium Alloy

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Abstract: The hot deformation of TA15 titanium alloy was studied by the hot compression test on the Gleeble-3800 thermal simulation equipment. The true stress-strain curves of TA15 titanium alloy in the temperature range of 1123-1223K and the strain rate range of 0.001-1s⁻¹ were obtained. The results show that the flow stress increases with decreasing temperature, and increases as the strain rate increases. And the deformation process is accompanied by work hardening and dynamic recovery and dynamic recrystallization. Based on the true stress-strain curves of TA15 titanium alloy, the Arrhenius-typed constitutive equation was established. The thermal deformation activation energy of TA15 titanium alloy with a strain of 0.2 is 746.27kJ/mol.

Introduction

TA15 titanium alloy has the advantages of high specific strength, low density, high corrosion resistance and good welding performance[1-4], and is widely used in aerospace, marine engineering and other fields, such as the complex force hermetically sealed cabin, beam frame and other key components[5-8].TA15 titanium alloy is a near-alpha titanium alloy with a nominal composition of Ti-6Al-2Zr-1Mo-1V. It is found that TA15 titanium alloy is very sensitive to temperature and strain rate during the forming process[9-1].

The microstructural evolution and deformation of TA15 titanium alloy have been studied by scholars.Li et al. established a unified mechanism material model of TA15 titanium alloy based on the softening mechanism of recrystallization and damage, and determined the optimal forming temperature range of 1023K~ 1173K for TA15 hot stamping[9]. Zhang et al. found that the peak stress σp, steady-state stress σres, peak strain εp and steady-state strain εres have linear relationships with the Zener - Hollomon parameter, Z[10]. Li et al. studied the effect of deformation temperature and strain rate on flow stress and established a TA15 processing map[11].

The flow stress of titanium alloys is often predicted by using the Arrhenius type of equations[12-16]. In this paper, the true stress-strain curve of TA15 titanium alloy in the temperature range of 1123-1223K and the strain rate range of 0.001-1s⁻¹ were obtained by hot compression tests, and the constitutive equation was established based on the curve, and the thermal deformation microstructure of TA15 titanium alloy was analyzed to provide guidance for the hot working process of TA15 titanium alloy[17-23].

In this paper, the thermal deformation of TA15 titanium alloy was represented by setting different temperatures and strain rates. The temperature of hot compression tests was controlled below the phase change point. Flow stresses were further analyzed on the basis of the test results. A comprehensive model of temperature, strain rate and flow stresses was developed. Finally, the model was verified for reliability[24-26].
**Procedure**

The experimental material is cast TA15 titanium alloy, the chemical composition of the alloy is shown in Table 1, the main elements are Ti, Al, V, Zr, Mo, Fe. The original microstructure of the alloy is shown in Figure 1, which is a typical near-alpha microstructure consisting of α and β phases, and the crystal grain consists of lamellar (α+β) phases.

|    |  |  |  |  |  |  |  |  |  |
|----|---|---|---|---|---|---|---|---|
| Al | V | Fe | Si | Zr | Mo | C  | N  | O  |
| 5.5-6.8 | 0.8-2.5 | ≤0.3 | ≤0.15 | 1.5-2.5 | 0.5-2.0 | ≤0.13 | ≤0.05 | ≤0.16 | Bal.

Table 1 Composition of TA15 titanium alloy (wt%)

Isothermal compression simulation tests are used to study the deformation and microstructure evolution of materials at high temperatures. Isothermal compression tests of TA15 titanium alloy were performed on a Gleeble-3800 thermal simulator, and the height of the samples was reduced by 60% in the deformation temperature range of 1123-1223K and the strain rate range of 0.001-1s⁻¹. Cylindrical specimen of TA15 titanium alloy with a diameter of 8 mm and a height of 12 mm were fabricated. The appearance of the specimen before and after deformation is shown in the Figure 2a. Before hot compression, the samples would be heated and held for 5 min at a heating rate of 5 K/s, and then the experiments will be carried out at the corresponding strain rate. Finally, the samples would be water quenched immediately after the compression experiments to maintain the high temperature deformation microstructure. Heat treatment graph of TA15 titanium alloy compression test shown in Figure 2b.

Figure 2 The appearance of specimens and the thermal compression process; (a) the appearance of specimens before and after deformation; (b) heat treatment graph in the thermal compression processing.
Results and Discussion

1. The flow stress characteristics of flow stress

The stress-strain curves of TA15 titanium alloy under different deformation conditions (1123K, 1173K, 1223K) are shown in Figure 3. As shown in the figure, when the temperature is constant, the peak stress increases as the strain rate increases. This is due to the fact that as the strain rate increases, the effect of work hardening is greater than that of $\alpha$ phase recrystallization. As the strain rate decreases, the flow stress reaches a stable state after the stress reaching its peak, when the strain rate decreases and the deformation time increases, the dynamic recrystallization are equivalent to the work-hardening effect[27-28].

![Figure 3](image-url) True-stress-strain curves at different temperature: a)1123K, b)1173K, c)1223K

2. The flow stress characteristics of flow stress

The Arrhenius constitutive model proposed by Sellars and and McTegart can accurately describe the relationship between deformation temperature, strain rate and flow stress, and is therefore widely used in the field of plastic forming[29-30]. The model can be expressed in three different ways.

$$\dot{\varepsilon} = A \sigma^n \exp\left(-\frac{Q}{RT}\right)$$  \hspace{1cm} (1)

$$\dot{\varepsilon} = A_2 \exp(\beta \sigma) \exp\left(-\frac{Q}{RT}\right)$$  \hspace{1cm} (2)

$$\dot{\varepsilon} = A [\sinh \alpha \sigma]^n \exp\left(-\frac{Q}{RT}\right)$$  \hspace{1cm} (3)

where $\dot{\varepsilon}$ is the effective strain rate ($s^{-1}$), $\sigma$ is the flow stress (MPa), $T$ is the deformation temperature(K), $Q$ is the thermal deformation activation energy$(J/mol)$, $R$ is the universal gas constants $(8.314 \, J/mol \cdot K)$, $A$, $A_1$, $A_2$, $\alpha$, $\beta$, $n$ and $n_1$ are the material constants, and $\alpha = \frac{\beta}{n_1}$.

Eq. (2) is applicable to low stress level with $\alpha \sigma < 0.8$, and Eq. (3) is applicable to high stress level with $\alpha \sigma > 1.2$.

Taking the logarithm of both sides of Eq. (1) and (2), respectively yields:

$$\ln \dot{\varepsilon} = \ln A_1 + n_1 \ln \sigma - \frac{Q}{RT}$$ \hspace{1cm} (4)

$$\ln \dot{\varepsilon} = \ln A_2 + \beta \sigma - \frac{Q}{RT}$$ \hspace{1cm} (5)

The material constants are solved based on the experimental data obtained from the thermal compression tests. Take the true strain of 0.2 as an example to introduce the process of solving the material constants. The test data were fitted based on Eq.(4) and Eq.(5) to obtain two sets of fitted curves. Then, the values of $n_1$ and $\beta$ are obtained by solving the average value of the slope of the fitted
The strain-compensated Arrhenius-type constitutive model will change. Therefore, multiple strains of the deformation were chosen to modify the Arrhenius constitutive model. And the strain was selected in the range of 0.05 to 0.9 with an interval of 0.05. Then, 18 groups of model parameters were obtained by the process of solving. A ninth-order polynomial is used to represent the effect of strain on the material constants, as shown in Figure 4. The correlation coefficients of the polynomial fitting results show that the fitting accuracy is high because all four material constants are above 0.99. The coefficients of the polynomial are shown in the Table 3.

![Table 3 Constitutive model parameters of TA15 titanium alloy](image)
Figure 4 Variations of material constants of: a) n, b) $\alpha$, c) Q and d) $\ln A$ with strain

Table 3 Coefficients of the polynomial for $A$, $\alpha$, $n$, $Q$

|   | $\ln A$         | $\alpha$     | $n$     | $Q$       |
|---|-----------------|--------------|---------|-----------|
| A1| 112.07308       | $\alpha_1$  | 0.02038 | 4.12851   |
| A2| -502.08533      | $\alpha_2$  | -0.34552| 9.7485    |
| A3| 2058.66326      | $\alpha_3$  | 4.11098 | -216.97177|
| A4| 2942.91321      | $\alpha_4$  | -25.54035| 1898.88574|
| A5| -67412.25023    | $\alpha_5$  | 95.07253| -9234.04554|
| A6| 294948.31459    | $\alpha_6$  | 222.38349| 26834.93964|
| A7| -648887.42818   | $\alpha_7$  | 329.64746| -47485.7099|
| A8| 789145.61722    | $\alpha_8$  | 300.75517| 50058.85853|
| A9| -505220.90521   | $\alpha_9$  | 154.16507| -28864.5825|
| A10| 132993.83199    | $\alpha_{10}$| -33.99046| 7002.75768|

Typically, $R$ (Correlation coefficient) and AARE (average absolute relative error) are used to evaluate the correlation coefficient between the experimental and predicted values. Therefore, the accuracy of the established constitutive model was evaluated by calculating the $R$ and AARE factors, and the expression is as follows:

$$R = \frac{\sum_{i=1}^{n} (P_i - \bar{P})(E_i - \bar{E})}{\sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2 \sum_{i=1}^{n} (E_i - \bar{E})^2}}$$

$$AARE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{P_i - E_i}{E_i} \right| \times 100$$

(11) (12)
where $P_i$ is the predicted value, $E_i$ is the experimental data, $n$ is the number of data point. The comparison results of the experimental data and the predicted values are shown in the Figure 4. The correlation coefficient ($R$) of all deformation conditions is 0.98328.

![Figure 4](image)

**Figure 4** Correlation between the experimental and predicted flow stress data

![Figure 5](image)

**Figure 5** Comparison of the experimental and predicted flow stress at different temperatures: a) 1123K, b) 1173K, c) 1223K

The experimental and predicted flow stress at different temperatures are shown in Figure 5. The average absolute relative error (AARE) at 1123K and 1173K is 9.8%, and the AARE at all temperature is 14.5%, which indicates that constitutive equation is well predicted for TA15 titanium alloy at 1123K and 1173K.

**Conclusion**

This paper investigates the flow behavior of TA15 titanium alloy through a set of hot compression test and establishes the constitutive equation. Conclusions were obtained as follows:

- TA15 titanium alloy stress is very sensitive to temperature and strain rate, the value increases with increasing strain rate and decreasing temperature. The test result curve is a typical flow curve, and the Arrhenius equation can be used to establish the constitutive model.
- An Arrhenius model based on the effect of strain was established to describe the flow stress of TA15 titanium alloy. The experimental and predicted results show that the strain-compensated Arrhenius model predicts better flow behavior at 1123K and 1173K.
- The deviation of the predicted value of 1223K from the experimental value is influenced by the phase transformation.
- The results of the above research provide a certain basis for the hot forming of TA15 titanium alloy, and the constitutive equation can be used for FE simulation calculations.
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