HOT DEFORMATION BEHAVIOR OF TC18 TITANIUM ALLOY

by

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Short paper
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Isothermal compression tests of TC18 titanium alloy at the deformation temperatures ranging from 25 °C to 800 °C and strain rate ranging from 10^{-4} to 10^{-2} s^{-1} were conducted by using a WDW-300 electronic universal testing machine. The hot deformation behavior of TC18 was characterized based on an analysis of the true stress-true strain curves of TC18 titanium alloy. The curves show that the flow stress increases with increasing the strain rate and decreases with increasing the temperature, and the strain rate play an important role in the flow stress when increasing the temperatures. By taking the effect of strain into account, an improved constitutive relationship was proposed based on the Arrhenius equation. By comparison with the experimental results, the model prediction agreed well with the experimental data, which demonstrated the established constitutive relationship was reliable and can be used to predict the hot deformation behavior of TC18 titanium alloy.

Key words: *hot deformation, TC18 titanium alloy, flow stress, constitutive relationship*

Introduction

With the rapid advancement of industry in recent years, the requirement that combination of properties of materials should be superior to the capabilities of traditional materials had been proposed, so many scholars have conducted research on new materials [1], and some new research methods were applied [2]. Similarly, the mechanical properties of solid materials at the high temperature had been deeply studied in the area of aviation and aerospace. Titanium alloys had been studied by several investigators because of their use in aero-engine, gas turbine and other applications due to their low densities, excellent fracture toughness, good creep and erosion resistance in various kinds of environment and high temperature capability [3]. For example, titanium alloys were widely used in military domain because of its good adiabatic shear properties, the application of aerospace field were mainly due to its high specific strength. TC18 (BT22) titanium alloy was α-β titanium alloy with high strength and good weldability, the strength coefficient of welded joint of TC18 titanium alloy can reached 90%. It was developed by the former Soviet Union Institute of Aeronautical Materials in 1974. It was important significance by establishing suitable constitutive relationship to indicate hot deformation behavior of TC18 titanium alloy. The constitutive relationship was a collection of representations that described the relation of thermodynamic parameters of material during hot deformation process. The relationship was widely used in the finite

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element simulation and optimizing process parameters. Over the past few years, some investigators tried to predict the constitutive relationships for some alloys using the regression method, including typical Arrhenius constitutive equations based on exponential law, power exponential law and hyperbolic sine law, respectively [4]. But most of applied constitutive relationships were expressed steady stress or peak stress, and the direct impact of strain was ignored [5], so that it leaded to some lack of application for these models. In this paper the hot deformation behavior of TC18 titanium alloy was studied by isothermal compression test. Considering the effect of strain, an improved constitutive relationship was established based on the hyperbolic-sine Arrhenius equation and the constitutive model proposed by ref. [6]. The constitutive relationship was accurate and efficient in terms of predicting the hot deformation behavior of TC18 titanium alloy.

Experimental procedures

The material of TC18 titanium alloy was provided by Northwest Institute for Nonferrous Metal Research, China. The nominal composition of TC18 titanium alloy was Ti-5Al-5Mo-5V-1Cr-1Fe, the chemical composition was shown in tab. 1. The specimens were machined into cylindrical shape with 6 mm in diameter and 6 mm in length using linear cutting machine and lathe, as shown in fig. 1(a).

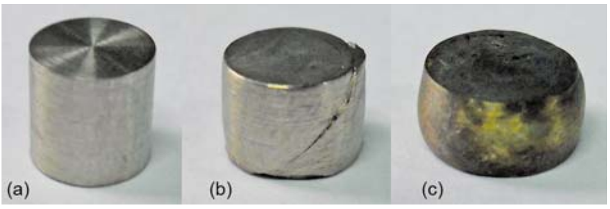

Figure 1. The pattern of (a) original specimen, (b) cracked specimen after test of 25 °C or 300 °C, and (c) deformed specimen after test of 600 °C or 800 °C

The isothermal compression test was carried on WDW-300 electronic universal testing machine. GW-1200 A controller and high-temperature furnace were used to provide an accurate temperature control and measurement during testing. In order to establish the constitutive relationship to delineate hot deformation behavior of TC18 titanium alloy, a series of tests were conducted at strain rate of 10^{-4}, 10^{-3}, and 10^{-2} s^{-1} and at deformation temperature of 25, 300, 600 and 800 °C. The heat preservation time of specimens was three minutes after the specimens were heated to the experimental temperature in order to obtain a uniform deformation temperature. The force-deformation curves were recorded automatically during isothermal compression test. Specimens were water quenched immediately after the completion of hot compression test in order to retain hot deformation organization of the material. At least 2 times repetitive experiments of TC18 titanium alloy were carried in each working condition. Two valid experimental data of good reproducibility were taken average.

Table 1. Chemical composition of TC18 titanium alloy

Element	Ti	Al	Mo	V	Cr	Fe
Percent weight composition	Bal.	4.5%-5.9%	4.0%-5.0%	4.0%-5.5%	0.5%-2.0%	0.5%-1.5%

Results and discussion

Stress-strain behavior

The typical true stress-true strain curves of TC18 alloy obtained from hot compression test were presented in fig. 2.

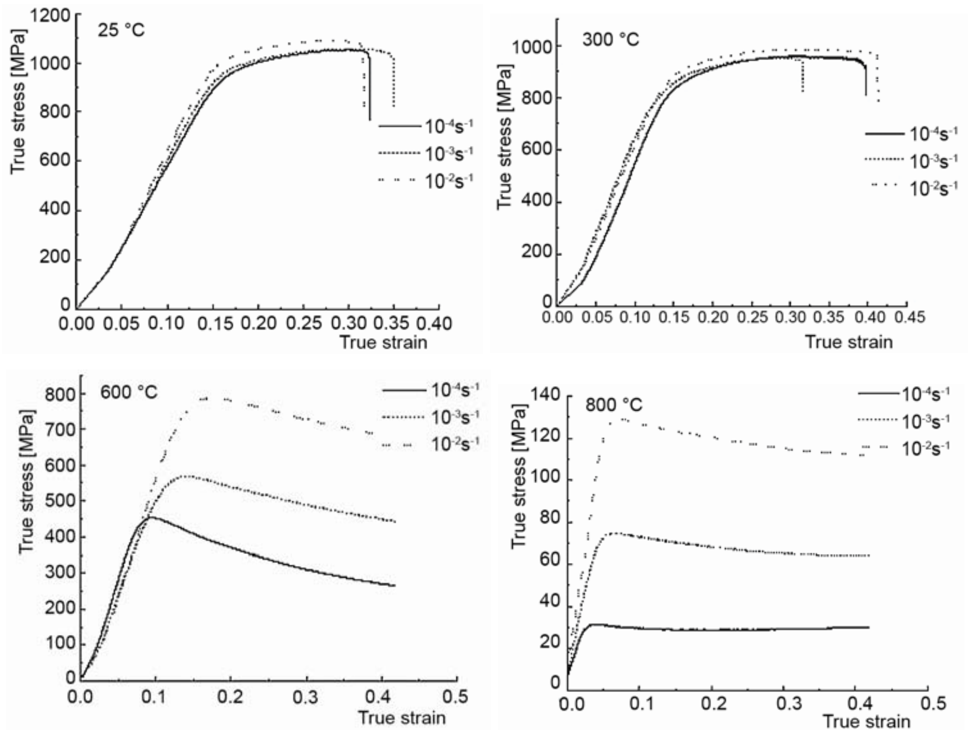

Figure 2. True stress-true strain curves of TC18 titanium alloy

As seen in fig. 2, the flow stress increased with increasing strain rate at the same temperature. The strain rate effect was appeared from this material, and this effect was more obvious at higher temperature. The flow stress decreased with increasing temperature at the same strain rate. For the true stress-strain curves at room temperature and 300 °C, the flow stress continued increased with increasing strain until the alloy was damaged, it showed that the strain-hardening effect of alloy was greater than temperature softening effect in this temperature stage. The cracked specimen was performed in fig. 1(b), it was similar with fracture pattern of most metals which appeared a typical fracture of 45-degree angle with axis of the specimens. As for the true stress-strain curves at 600 and 800 °C, the flow stress dropped continuously and tended to the steady stress after the peak stress with increasing strain, it indicated that the temperature softening effect dominated in the temperature stage. The deformed specimen was shown in fig. 1(c), it was compressed into a flat drum. Comparing the experimental curves at 600 °C with at 800 °C, after the peak stress, the flow stress of TC18 titanium alloy dropped quickly at temperature of 600 °C. The reason was that dynamic softening effect which containing dynamic recovery and re-crystallization softening strengthened with decreasing temperature [7]. At the temperature of 800 °C, the peak stress was almost equal to the steady stress mainly because with increasing temperature, thermal activation effect strengthening, atomic activity increasing and critical shear stress of varieties of slip systems decreasing, the peak stress of alloy decreased [8].

Constitutive relationship

Metal and alloy had thermal activation process during hot deformation. Based on the Arrhenius equation, Sellars and Tegart [9] established a generic hyperbolic-sine constitutive relationship of the activation energy, strain rate, temperature and flow stress to describe the deformation behavior:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp[-Q/(\mathrm{R}T)] \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, σ – the flow stress, T – the absolute temperature, Q – the activation energy of deformation, R – the gas constant (8.314 $\mathrm{Jmol^{-1}K^{-1}}$), n – the stress exponent, α – the stress adjustment factor [$\mathrm{MPa^{-1}}$], and A – the constant.

Because of the flow stress of TC18 titanium alloy continuous changing with increasing strain, the hyperbolic-sine constitutive relationship based on the Arrhenius equation not containing strain, the improved constitutive equation was established necessarily to accurately describe the relationship of true stress-strain of TC18 titanium alloy. The followed constitutive relationship containing strain based on the Arrhenius equation was proposed:

$$\ln[\sinh(\alpha\sigma)] = B_0 \ln\dot{\varepsilon} + B_1(1/T) + B_2(\ln\varepsilon)^2 + B_3\ln\varepsilon + B_4 \tag{2}$$

where $\dot{\varepsilon}$ is the strain, B_0 and B_1 are constants, and B_2, B_3, and B_4 – functions of temperature T, they can be seen as constants at the lower temperature. Multivariable regression analysis was used to calculate these parameters.

When temperature was lower ($T \leq 573$ K, *i. e.* at temperature of 25 °C and 300 °C): $B_0 = 0.01665$, $B_1 = 83.21$, $B_2 = -0.311$, $B_3 = -0.771$, and $B_4 = -0.372$.

When temperature was higher ($T \geq 873$ K) *i. e.* at temperature of 600 °C and 800 °C): $B_0 = 0.3568$, $B_1 = 13876.76$, $B_2 = 0.000968T - 0.98285$, $B_3 = 0.00505855T - 5.3653$, and $B_4 = 0.00525\,T - 17.43325$.

Then the constitutive relationship of TC18 titanium alloy was followed. At lower temperature ($T \leq 573$ K):

$$\ln[\sinh(0.0010256\sigma)] = 0.01665\ln\dot{\varepsilon} + 83.21(1/T) - 0.311(\ln\varepsilon)^2 - 0.771\ln\varepsilon - 0.372 \tag{3}$$

At higher temperature ($T \geq 873$ K):

$$\ln[\sinh(0.004333\sigma)] = 0.3568\ln\dot{\varepsilon} + 13876.76(1/T) + B_2(\ln\varepsilon)^2 + B_3\ln\varepsilon + B_4 \tag{4}$$

$B_2 = 0.000968\,T - 0.98285$, $B_3 = 0.00505855\,T - 5.3653$, $B_4 = 0.00525\,T - 17.43325$.

The experimental curves and calculated flow stress by eqs. (3) and (4) were drawn in fig. 3. It showed that the calculated flow stress data were consistent well with experimental curves. The data points of error more than 10% of the calculated stress were rarely even at the higher temperature. These indicated that the established constitutive relationship can more accurately describe the flow stress behavior of TC18 titanium alloy, the relationship can provide material model for finite element simulation and optimizing process parameters.

Conclusions

Isothermal compression tests of TC18 titanium alloy at the deformation temperatures ranging from 25 °C to 800 °C and strain rate ranging from 10^{-4} to $10^{-2}\mathrm{s^{-1}}$ were conducted to investigate the hot deformation behavior of TC18. The true stress-true strain curves of TC18 titanium alloy was derived, from which it can be seen that the flow stress increases with increasing the strain rate and decreases with increasing the temperature, and the strain rate play an important role in the flow behavior of TC18 when increasing the temperatures.

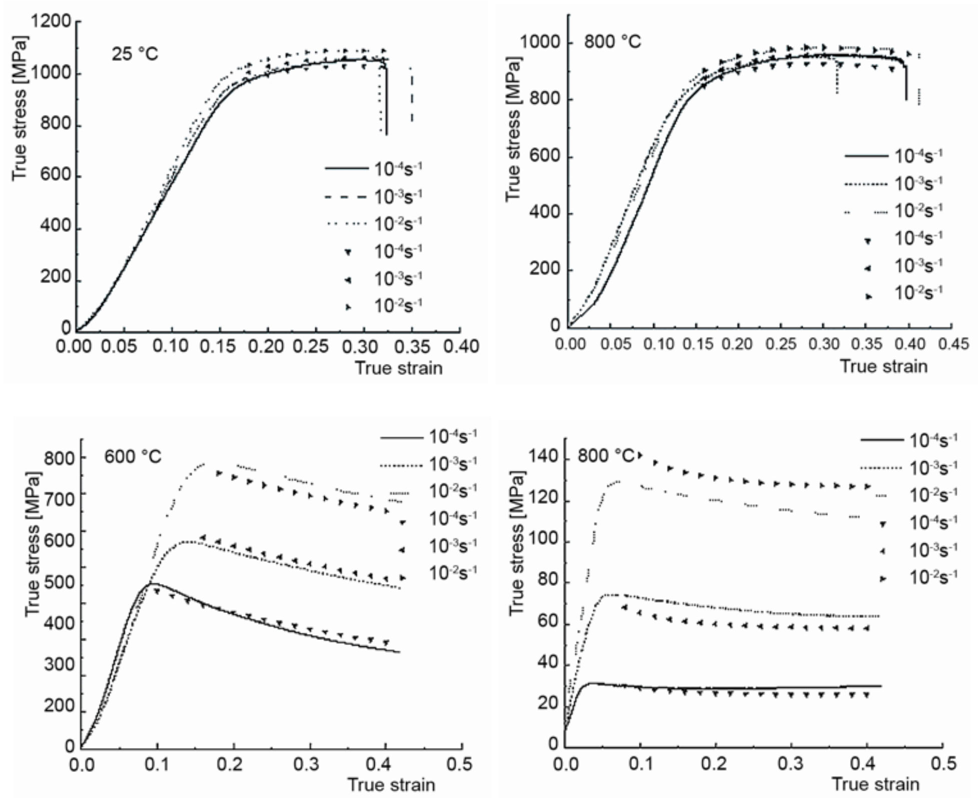

Figure 3. The calculated flow stress comparing with the experimental data

An improved constitutive relationship was presented by considering the effect of strain on the mechanical properties of the alloy based on the Arrhenius equation. A good agreement between the model prediction and the experimental data was obtained, which indicated the proposed constitutive model in the current study can be used to describe the hot deformation behavior of TC18 titanium alloy at elevated temperatures.

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