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Acquiring a Novel Constitutive Equation of a TC6 Alloy at High-Temperature Deformation

Miaoquan Li, Shenhui Cheng, Aiming Xiong, Hairong Wang, Shaobo Su, and Lichuang Sun

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The TC6 alloy produced in Baoji nonferrous metals work, Xian, China, is one of the best titanium alloys with good resistance against heat and corrosion and is widely used in the aviation and aerospace industries. In this paper, isothermal compression tests were conducted on the TC6 alloy in the Thermecmastor Z simulator, at temperatures between 800 and 1040 °C at strain rates between 0.001 and 50 s^{-1} to a 50% height reduction. The experimental results are presented as variations of flow stress with deformation temperature, strain rate, and strain. On the basis of the present experimental results and deformation behavior, a constitutive equation for the TC6 alloy was proposed by employing an Arrhenius-type equation. The activation energy of deformation (*Q*) and work-hardening index (*n*) are found to be a function of strain. The present equation is in good agreement with the experimental data.

Keywords constitutive equation, flow stress, hot compression, titanium alloy

1. Introduction

A constitutive equation that expresses the correlation between deformation behavior and process parameters is important in investigating the deformation behavior of alloys and in optimizing their performance. In establishing a constitutive equation, the first step is to consider the micromechanisms that occur during deformation, including the movement of dislocations, slip step formation, static and dynamic recovery, and recrystallization (Ref 1-4). The next step is to construct a numerical model using an artificial neural network (Ref 5, 6). The third step considers the correlation between the flow stress and process parameters (Ref 7, 8). The latter is easily applied in practice because only a few physical variables must be measured.

The TC6 alloy is a new titanium alloy with two phases. It possesses good ductility and toughness, and has a high relative strength and good resistance against heat and corrosion. The service temperature of the TC6 alloy can reach 450 °C. The TC6 alloy is widely used to manufacture important components, for example, aerofoil blades and disks in the aviation and aerospace industries.

In this research, isothermal compression tests were conducted on the TC6 alloy in the Thermecmastor-Z simulator (Japan) at temperatures between 800 and 1040 °C at strain rates between 0.001 and 50 s^{-1} up to a 50% height reduction of the sample. According to the present experimental results, the effect of process parameters on flow stress is investigated and a constitutive equation for the TC6 alloy is established utilizing an Arrhenius-type equation.

Miaoquan Li, Shenhui Cheng, and **Aiming Xiong,** College of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an, 710072, People's Republic China; and **Hairong Wang, Shaobo Su,** and **Lichuang Sun,** Xi'an Aero-engine Company Group Ltd., Xi'an, 710021, People's Republic of China. Contact e-mail: honeymli@nwpu.edu.cn.

2. Experimental Procedures

2.1 Material

The TC6 alloy was obtained as a round bar 42 mm in diameter. The chemical composition is shown in Table 1. The heat treatment procedure before isothermal compression consisted of the following steps: heated to 870 °C and soaked for 1 h; the temperature adjusted to 650 °C with the sample soaked for an additional 2 h; and then cooled in air to room temperature. Cylinder specimens, 8 mm in diameter and 12 mm in height, were machined from the heat-treated bars, and the cyl-

Table 1 Chemical composition of a TC6 titanium alloy (wt.%)

Al	Cr	Fe	Mo	Si	Ti
6.29	1.42	0.42	2.71	0.33	Balance

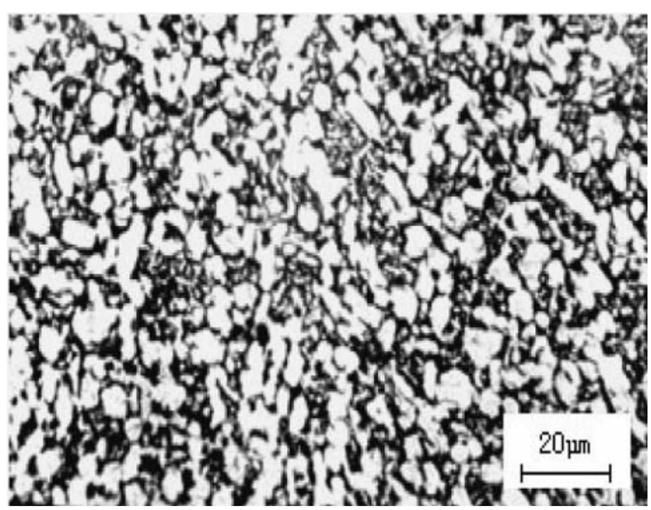

Fig. 1 Optical micrograph of a TC6 alloy before deformation

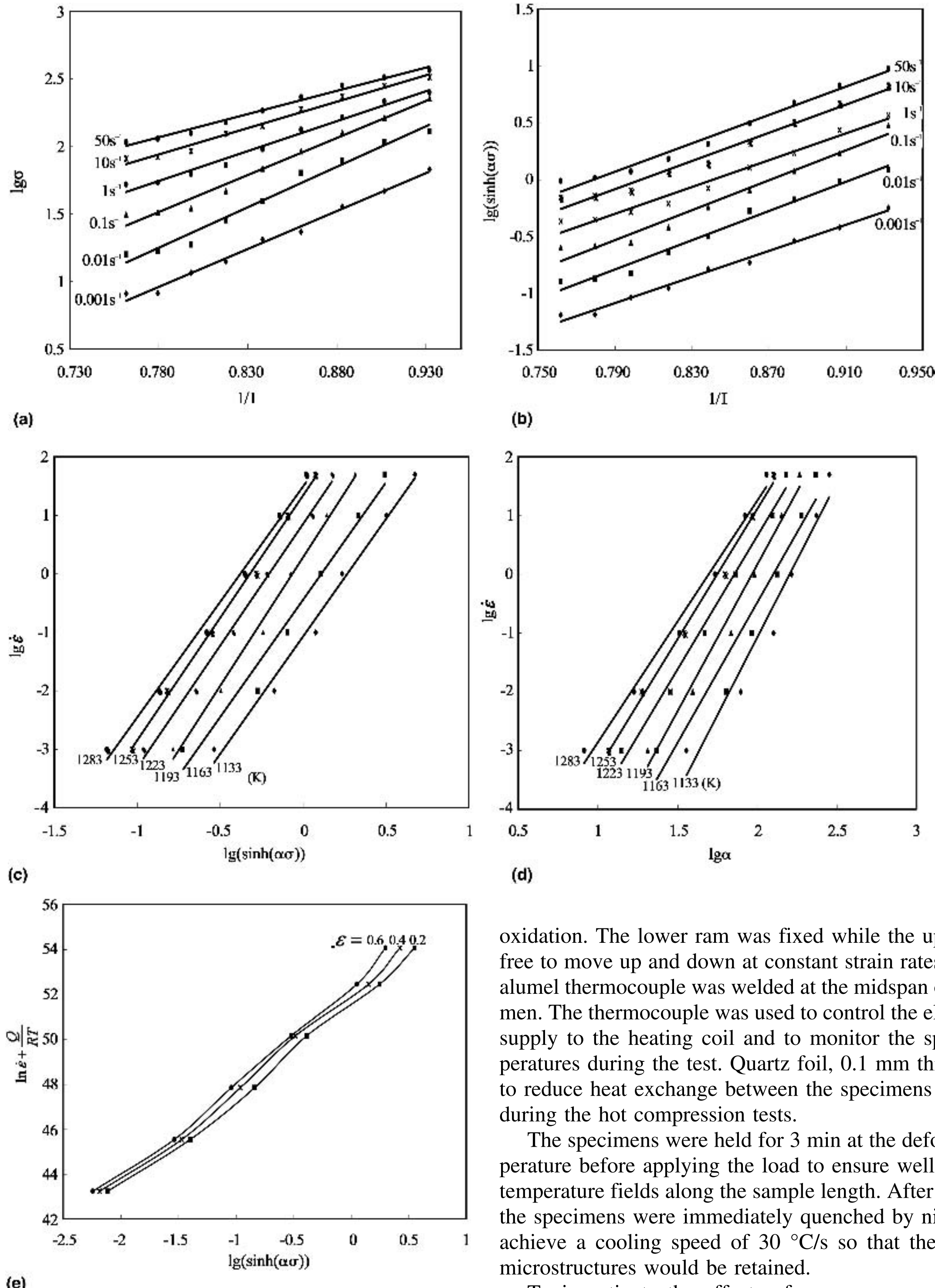

Fig. 2 Variation of flow stress with process parameters

inder ends were grooved for retention of the glass lubricants during hot compression testing.

2.2 Hot Compression

The isothermal compression experiments were conducted at a constant strain rate on the Thermecmastor-Z simulator for hot working. The specimens and compression rams were heated by high-frequency induction under vacuum conditions to avoid oxidation. The lower ram was fixed while the upper ram was free to move up and down at constant strain rates. A chromel-alumel thermocouple was welded at the midspan of each specimen. The thermocouple was used to control the electric current supply to the heating coil and to monitor the specimen temperatures during the test. Quartz foil, 0.1 mm thick, was used to reduce heat exchange between the specimens and the rams during the hot compression tests.

The specimens were held for 3 min at the deformation temperature before applying the load to ensure well-proportioned temperature fields along the sample length. After compression, the specimens were immediately quenched by nitrogen gas to achieve a cooling speed of 30 °C/s so that the as-deformed microstructures would be retained.

To investigate the effects of process parameters on flow stress and deformation behavior, nominal deformation temperatures between 800 and 1040 °C were used. The strain rate was varied between 0.001 and 50 s^{-1} at each temperature. Isothermal compression tests were performed to 50% reduction in height for each combination of deformation temperatures and strain rates.

3. Experimental Results and Constitutive Equation

Figure 1 illustrates the microstructure of as-received TC6 alloy.

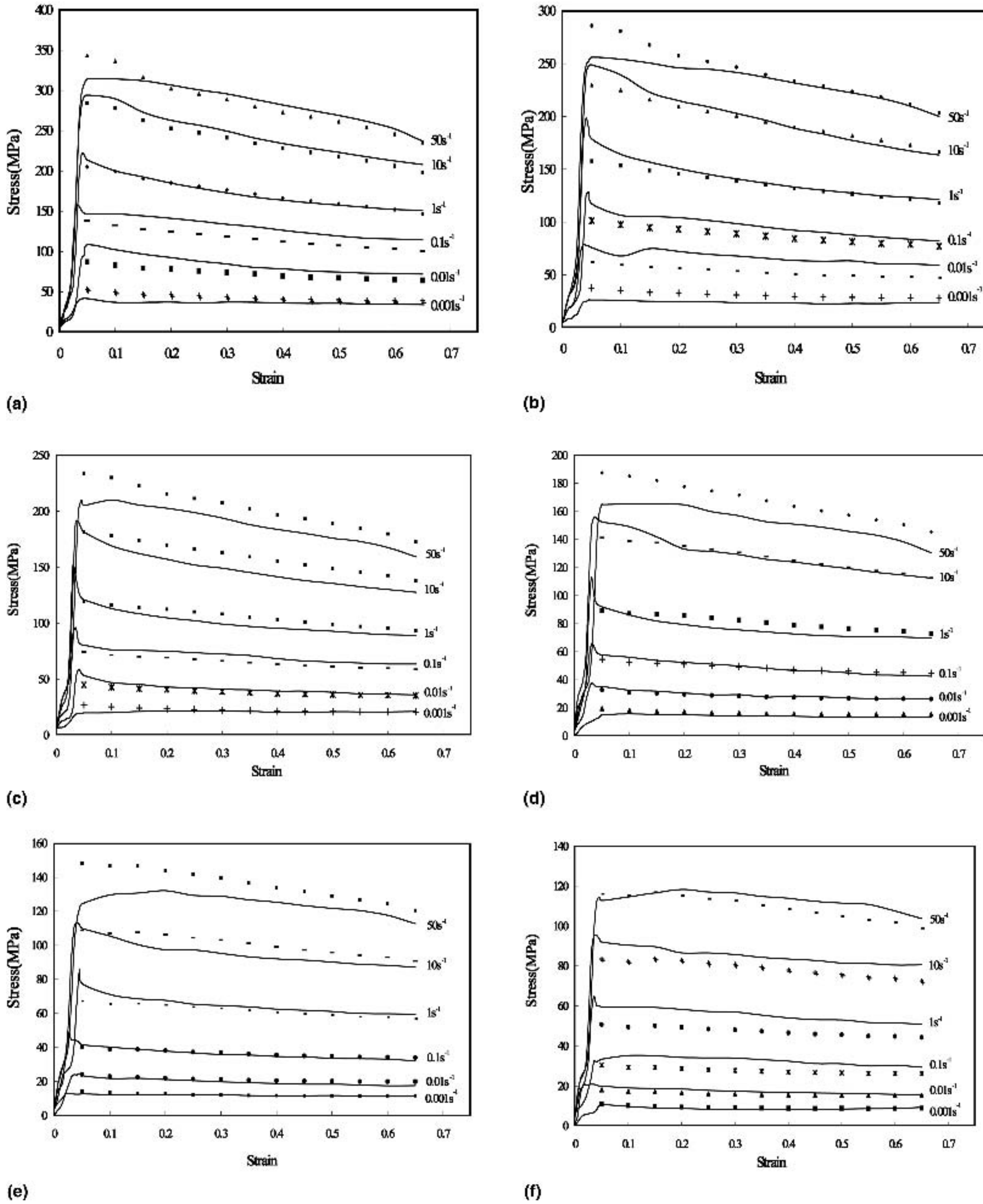

Fig. 3 Comparison of the calculated results (real line) of flow stress with the experimental (dotted line): (a) 860 °C, (b) 890 °C, (c) 920 °C, (d) 950 °C, (e) 980 °C, and (f) 1010 °C

Figure 2(a) shows how the log σ varies with strain-rate ($\dot{\varepsilon}$) and deformation temperature ($1/T$). Figure 2(b) shows how the log sinh($\alpha\sigma$)varies with strain-rate ($\dot{\varepsilon}$) and deformation temperature ($1/T$), where α is 0.008 MPa^{-1}. Figured 2(c) and (d) show how log $\dot{\varepsilon}$ varies with log sinh($\alpha\sigma$) and/or log σ at different deformation temperatures. Figure 2(e) shows how the:

$$\left(\log \dot{\varepsilon} + \frac{Q}{\mathrm{R}T}\right)$$

varies with log sinh($\alpha\sigma$) and/or log σ at different strains. The stress-strain curves obtained during hot compression tests of the TC6 alloy at elevated temperature are shown in Fig. 3 (i.e., the dotted line).

When a constitutive equation is used to express deformation behavior of a material, the "sinh-Arrhenius" equation (Eq 1) is generally used to describe the flow stress and deformation state:

$$\bar{\dot{\varepsilon}} \exp\left(\frac{Q}{\mathrm{R}T}\right) = A\sinh\,(\alpha\sigma)^{n} \qquad \text{(Eq 1)}$$

where $\bar{\dot{\varepsilon}}$ is the equivalent strain rate, σ is the flow stress (MPa), Q is the activation energy of deformation (kJ/mol), R is the gas constant (kJ/mol K), T is absolute temperature (K), and A, α, and n are material constants.

Table 2 Variation of α, *Q*, ln *A*, and *n* with equivalent strain

$\bar{\varepsilon}$	$\alpha \times 10^{-2}$, MPa	*Q*, kJ/mol	ln *A*	*n*
0.05	0.589	572.3	58.9	4.40
0.10	0.609	559.0	57.5	4.30
0.15	0.694	540.1	55.0	4.18
0.20	0.769	534.6	54.0	4.11
0.25	0.791	530.0	53.5	4.08
0.30	0.810	523.3	52.8	4.07
0.35	0.842	519.1	52.3	4.06
0.40	0.850	514.3	51.9	4.09
0.45	0.859	511.8	51.7	4.11
0.50	0.877	511.0	51.6	4.14
0.55	0.900	509.3	51.4	4.15
0.60	0.949	508.4	51.1	4.16
0.65	0.995	508.6	51.0	4.21

From Eq 1, flow stress is related to deformation temperature and strain rate. It is well known that flow is instantaneous during hot deformation and is affected by the thermo-mechanical behavior of the material. In establishing the constitutive equation for TC6, the constants *Q*, *A,* and *n* are assumed to be a function of strain.

Using the experimental data for TC6 from this study, the constants α, ln *A*, *n*, and *Q* for a particular set of deformation conditions at a strain level can be obtained from Table 2.

According to the experimental results shown in Table 2, Eq (2a-d) can be used to compute the constants α, *Q*, ln *A*, and *n*:

$$\alpha = \begin{cases} 2.7818\bar{\varepsilon}^4 - 2.3255\bar{\varepsilon}^3 + 0.6432\bar{\varepsilon}^2 \\ - 0.0565\bar{\varepsilon} + 0.0074\ (\bar{\varepsilon} \le 0.35) \\ -0.3733\bar{\varepsilon}^4 + 0.7756\bar{\varepsilon}^3 - 0.5753\bar{\varepsilon}^2 \\ + 0.1848\bar{\varepsilon} - 0.0134\ (\bar{\varepsilon} > 0.35) \end{cases} \quad \text{(Eq 2a)}$$

$$Q = \begin{cases} -14{,}667\bar{\varepsilon}^4 + 10{,}089\bar{\varepsilon}^3 - 1666.70\bar{\varepsilon}^2 \\ - 218.10\bar{\varepsilon} + 586.71\ (\bar{\varepsilon} \le 0.35) \\ 6848.50\bar{\varepsilon}^4 + 14{,}164\bar{\varepsilon}^3 + 10{,}957\bar{\varepsilon}^2 \\ - 3783.50\bar{\varepsilon} + 1005.60\ (\bar{\varepsilon} > 0.35) \end{cases} \quad \text{(Eq 2b)}$$

$$\ln A = \begin{cases} -3636.40\bar{\varepsilon}^4 + 2820.20\bar{\varepsilon}^3 - 663.33\bar{\varepsilon}^2 \\ + 22.90\bar{\varepsilon} + 59.14\ (\bar{\varepsilon} \le 0.35) \\ 969.70\bar{\varepsilon}^4 + 1983.80\bar{\varepsilon}^3 + 1501.80\bar{\varepsilon}^2 \\ - 502.15\bar{\varepsilon} + 144.59\ (\bar{\varepsilon} > 0.35) \end{cases} \quad \text{(Eq 2c)}$$

$$n = \begin{cases} -175.76\bar{\varepsilon}^4 + 138.38\bar{\varepsilon}^3 - 31.50\bar{\varepsilon}^2 \\ + 0.53\bar{\varepsilon} + 4.44\ (\bar{\varepsilon} \le 0.35) \\ 96.97\bar{\varepsilon}^4 + 185.05\bar{\varepsilon}^3 + 129.58\bar{\varepsilon}^2 \\ - 39.25\bar{\varepsilon} + 8.37\ (\bar{\varepsilon} > 0.35) \end{cases} \quad \text{(Eq 2d)}$$

where $\bar{\varepsilon}$ is equivalent strain in each case.

Substituting Eq 2a-d into Eq 1, the flow stress can be computed for each set of deformation conditions. Figure 3 shows the comparison between the calculated results and the experimental tests results for the TC6 alloy. The calculated results agree well with the experimental data.

4. Conclusions

From the experimental results of TC6 alloy, the correlation between deformation behavior and process parameters is significant. In establishing the constitutive equation for the TC6 alloy, the activation energy of deformation (*Q*) and the work-hardening index (*n*) are assumed to be a function of strain. On the basis of the present experimental results and the deformation characteristics of the TC6 alloy, a constitutive equation for TC6 is established by employing an Arrhenius equation. The calculated results are in good agreement with the experimental data.

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