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ARTICLE

Flow Stress Prediction for As-cast TC17 Titanium Alloy

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Abstract: The hot deformation behavior of as-cast TC17 titanium alloy was investigated by isothermal hot compression tests at temperatures of 1073~1373 K and strain rates of 0.01~20 s^{-1}. The four constitutive models, strain compensated Arrhenius-type (SCA), modified Arrhenius-type (MA), Johnson Cook (JC) and modified Johnson Cook (MJC), were used to represent the elevated temperature flow behavior of as-cast TC17 titanium alloy. The suitability levels of these models were evaluated by comparing the correlation coefficient R, average absolute relative error (AARE), and relative error. The results indicate that the JC model is inadequate to predict the flow stress of as-cast TC17 titanium alloy; the SCA model has the highest accuracy to descript of flow behavior of TC17 alloy in the $\alpha+\beta$ two-phase region in the studied range. While the MJC model exhibits the highest accuracy in the β single-phase region. Within the whole deformation temperature range, the SCA model proposed in this paper can more accurately conform to the high-temperature rheological curve of as-cast TC17 titanium alloy.

Key words: as-cast TC17 titanium alloy; constitutive model; flow stress

As a "β-rich" $\alpha+\beta$ titanium alloy, TC17 (Ti-5Al-2Sn-2Zr-4Mo-4Cr) titanium alloy has excellent mechanical properties, such as high tensile strength, excellent corrosion resistance, superior fracture toughness and deep hardenability. Therefore, TC17 titanium alloy is an ideal candidate material for fan blades and compressor disks of aircraft engine[1-3] and often used as material for shaft, frame and joint in large equipment, which bears great force[4-7]. However, TC17 titanium alloy is a difficult-to-deformation material, and the main processing mode of this alloy after ingot casting is multi-pass cogging for the purpose of breaking the coarse grains and eliminating casting defects such as segregation and shrinkage cavity.

Cogging is a very complex process involving high temperature, multi-pass and large deformation. Therefore, numerical simulation has come to be a common method to analyze and optimize the cogging parameters. The constitutive equations of materials are usually used as input conditions to describe the relationship between flow stress and deformation conditions (strain, strain rate and deformation temperature) in numerical simulation. The accuracy and simulation time are directly determined by the constitutive equation.

The main purpose of this investigation is to establish the suitable constitutive equation by comparative studying on different models to predict the high-temperature deformation behavior of TC17 titanium alloy. To achieve this, isothermal hot compression tests were carried out in a wide temperature range of 1073~1373 K and strain rate range of 0.01~20 s^{-1}. Then flow stress data were then employed to derive strain compensated Arrhenius-type (SCA), modified Arrhenius-type (MA), Johnson Cook (JC) and modified Johnson Cook (MJC) models. Finally, the suitability of these four models was evaluated by average absolute relative error (AARE), correlation coefficient (R) and relative error.

1 Experiment

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The initial dimension of as-cast TC17 titanium alloy bars is Φ540 mm×250 mm. A Gleeble 3500D thermal simulator was adopted to conduct the thermal compression experiment. The compressed samples are cylinders with Φ8 mm×12 mm, and the specimens before and after deformation are given in Fig.1.

Fig.2 is the microstructure of the as-cast TC17 titanium alloy bar. It can be seen that the original structure of as-cast TC17 titanium alloy is typical basket structure of coarse β phase interwoven and long α phase existing in β grain. The phase transition temperatures of as-cast TC17 titanium tests under different hot deformation parameters were provided: deformation temperature (K): 1073, 1113, 1153, 1223, 1298, 1373; strain rate (s^{-1}): 0.01, 0.1, 1, 10, 20; deformation degree: 60%.

The specimens were heated to the set deformation temperature at the heating speed of 10 °C/s by self-resistance induction current, and then held for 10 min. After the test, the deformed specimens were cooled by water. The deformed samples were cut along the axis by wire cutting. Thereafter, the specimens were ground by abrasive paper with grits of 400#, 800#, 1000#, 1500#, 2000# to eliminate the trace of wire cutting and then mechanically polished to mirror. Etchant solution contains HF, HNO_3, and H_2O with the volume proportion of 5:5:90, and corrosion time is 10~15 s. The microstructures of deformed samples were observed by the optical microscope.

Fig.1 Photo of samples before and after hot compression test

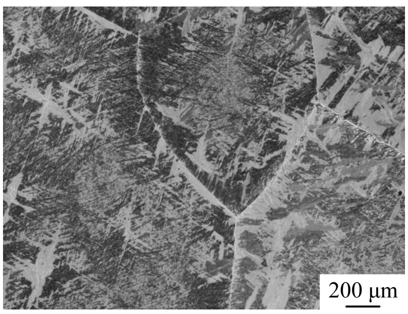

Fig.2 Microstructure of as-cast TC17 alloy

2 Results

2.1 Flow stress

Fig.3 is the flow stress curves of the TC17 alloy at different temperatures and strain rates. It can be seen from the figures that the flow stress curves of as-cast TC17 titanium alloy exhibit the following characteristics:

(1) At the beginning of deformation, the flow stress increases rapidly with the increase of strain.

(2) The flow stress reaches the peak value with the increase of deformation. Then with the increase of strain, the flow stress exhibits an obvious flow softening phenomenon and gradually tends to be stable, showing the characteristics of steady flow.

(3) As-cast TC17 titanium alloy is very sensitive to strain rate and deformation temperature. At a given temperature, the flow stress increases with the increase of strain rate. At a given strain rate, the flow stress decreases with the increase of deformation temperature.

(4) When the strain rate is higher than 10 s^{-1}, the high temperature flow stress curves of as-cast TC17 titanium alloy show a sharp drop after reaching the peak value, or there is an obvious discontinuous yielding phenomenon.

2.2 Strain compensated Arrhenius-type (SCA) model

Generally speaking, the thermal deformation behavior of materials is a process of thermal activation, and the effects of deformation temperature and strain rate on flow stress can be expressed by Arrhenius equation:

$$\dot{\varepsilon} = AF(\sigma)\exp(-\frac{Q}{RT}) \tag{1}$$

where, $F(\sigma)$ is expressed as:

$$F(\sigma) = \sigma^{n'} \quad \alpha\sigma < 0.8 \tag{2}$$

$$F(\sigma) = \exp(\beta\sigma) \quad \alpha\sigma > 1.2 \tag{3}$$

$$F(\sigma) = [\sinh(\alpha\sigma)]^n \quad \text{for all } \sigma \tag{4}$$

where, Q is the activation energy of deformation (J/mol); R is the constant of Proctor gas (8.314 $J\cdot mol^{-1}\cdot K^{-1}$); A, n', β, α and n are the material constants, $\alpha=\beta/n'$. In general, Eq. (2) is applicable to the thermal deformation process with low flow stress, exponential Eq. (3) is applicable to the thermal deformation process with high flow stress, and hyperbolic sine Eq. (4) is applicable to both cases. Fig.4 illustrates the microstructures of as-cast TC17 titanium alloy at the temperatures of 1073, 1298 K and strain rate of 0.01 s^{-1}. It can be seen that microstructure of as-cast TC17 titanium alloy consists of $\alpha+\beta$ grains in Fig.4a, and only coarse β grains can be found in Fig.4b. Therefore, the material constants in Eqs. (1)~(4) should be calculated for different phase regions.

It can be seen from Eqs. (1)~(4) that the effect of deformation degree on flow stress is ignored in the solution of the equation. However, it can be seen from Fig.3 that the deformation has a certain influence on the high-temperature flow stress of as-cast TC17 titanium alloy, especially in the $\alpha+\beta$ two-phase region. Therefore, the parameter values of α, n,

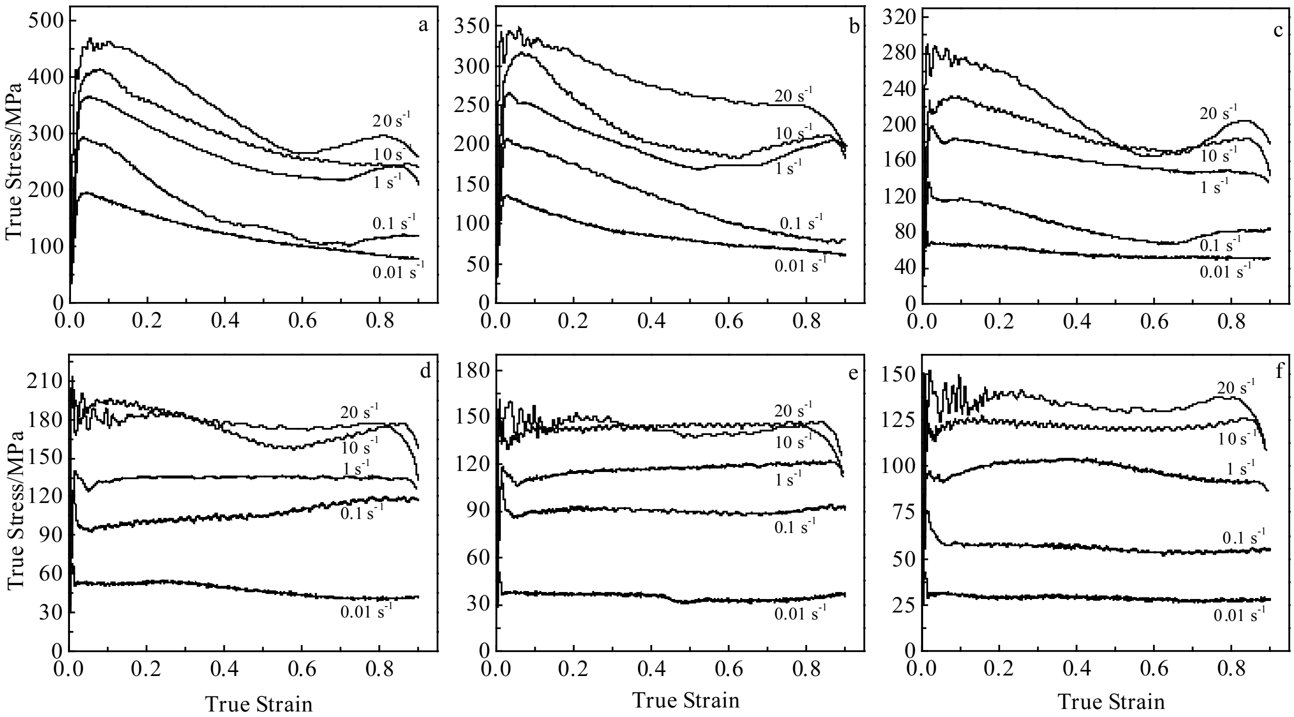

Fig.3 Flow stress-strain curves in the isothermal compression of as-cast TC17 titanium alloy: (a) 1073 K, (b) 1113 K, (c) 1153 K, (d) 1223 K, (e) 1298 K, and (f) 1373 K

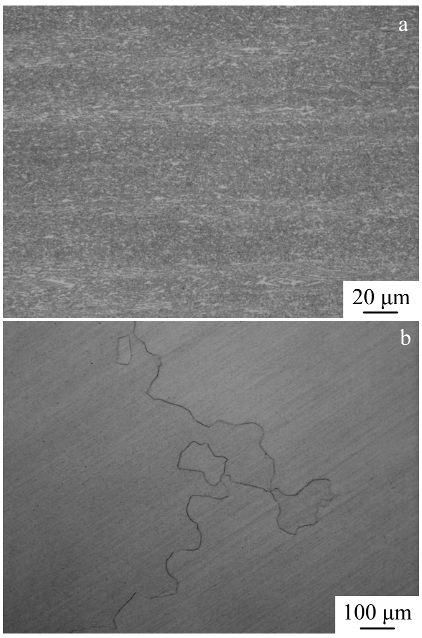

Fig.4 Microstructures of as-cast TC17 titanium alloy at 0.01 s^{-1}: (a) 1073 K and (b) 1298 K

Q and A should be the function of true strain[8,9]. In this paper, the strain range is 0.1~0.85, and the interval strain is 0.05. Polynomial is used to compensate the strain of α, n, Q and ln$A$. The order of the polynomial is chosen from 1 to 6, and then the appropriate polynomial degree is selected:

$$\begin{cases} \alpha = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 + C_4\varepsilon^4 + C_5\varepsilon^5 + C_6\varepsilon^6 \\ n = D_0 + D_1\varepsilon + D_2\varepsilon^2 + D_3\varepsilon^3 + D_4\varepsilon^4 + D_5\varepsilon^5 + D_6\varepsilon^6 \\ Q = E_0 + E_1\varepsilon + E_2\varepsilon^2 + E_3\varepsilon^3 + E_4\varepsilon^4 + E_5\varepsilon^5 + E_6\varepsilon^6 \\ \ln A = F_0 + F_1\varepsilon + F_2\varepsilon^2 + F_3\varepsilon^3 + F_4\varepsilon^4 + F_5\varepsilon^5 + F_6\varepsilon^6 \end{cases} \tag{5}$$

Table 1 and 2 are coefficients of the polynomial for α+β phase and single β phase, respectively. It can be seen that in the α+β two-phase region, α and n can obtain satisfactory results by using quintic polynomial fitting, while Q and ln$A$ can obtain high precision by using quartic polynomial fitting. In the single β phase, the values of n, Q and ln$A$ all need six order polynomial fitting, and α uses quintic polynomial fitting.

Fig.5 shows the comparison of the flow stress model between the SCA model and the test results. It can be seen that

Table 1 Coefficients of the polynomial for α+β phase

α	n	Q	ln$A$
C_0=0.00347	D_0=5.43701	E_0= 899.37835	F_0=94.66763
C_1=0.02091	D_1=0.60621	E_1=–2657.7179	F_1=–280.22893
C_2=–0.11086	D_2=–24.79574	E_2=7446.25261	F_2=781.72381
C_3=0.3311	D_3=95.18787	E_3=–10206.207	F_3=–1069.5707
C_4=–0.42669	D_4=–135.85272	E_4=4899.2148	F_4=512.32161
C_5=0.19304	D_5 =64.45668		

Table 2 Coefficients of the polynomial for β phase

α	n	Q	ln$A$
C_0=0.01002	D_0=5.18136	E_0=366.21887	F_0=32.4312
C_1=0.02331	D_1=-19.44336	E_1=–2650.64946	F_1=–249.57768
C_2=–0.14621	D_2=139.50555	E_2=20245.56921	F_2=1894.29989
C_3=0.41728	D_3=–466.9722	E_3=–71916.29367	F_3=–6705.93824
C_4=–0.51286	D_4=801.9095	E_4=128186.14354	F_4=11909.04557
C_5=0.22432	D_5=–692.50406	E_5=–111671.0678	F_5=–10330.58187
	D_6=238.96921	E_6=37933.8598	F_6=3492.71208

the flow stress determined by the above method is in good agreement with the test data. Only at 1298 K and 0.1 s^{-1}, the calculated results exhibit differences with the actual data.

2.3 Modified Arrhenius-type (MA) model

Taking logarithm of Eq. (1) and sorting it out, we can get:

$$F(\sigma) = A + B\ln\dot{\varepsilon} + \frac{C}{T} \tag{6}$$

By increasing the effect of plastic strain ε on flow stress at high temperature, the following equation can be obtained:

$$\varepsilon^{m'}\dot{\varepsilon}\exp(\frac{Q}{RT}) = A_1\sigma^n \tag{7}$$

Take logarithm from both sides of Eq. (7), and sort out:

$$\ln\sigma = \frac{1}{n}(\ln\dot{\varepsilon} + \frac{Q}{RT}) + \frac{m'}{n}\ln\varepsilon - \frac{\ln A_1}{n} \tag{8}$$

Zener-Hollomon parameter (temperature compensated strain rate parameter) is introduced to characterize the relationship between strain rate $\dot{\varepsilon}$ and deformation temperature T. Z is expressed as follows:

$$Z = \dot{\varepsilon}\exp(\frac{Q}{RT}) \tag{9}$$

Eq. (9) is brought into Eq. (8):

$$\ln\sigma = B_0 + B_1\ln Z + B_2\ln\varepsilon \tag{10}$$

In order to increase the accuracy of the equation, Eq. (10) is modified into follows[10]:

$$\ln\sigma = B_0 + B_1\ln Z + B_2(\ln Z)^2 + B_3\ln\varepsilon \tag{11}$$

where, B_0, B_1, B_2 and B_3 are material parameters. The results of hot compression test of as-cast TC17 titanium alloy are introduced into Eq. (11), and the corresponding material parameters can be obtained by multiple linear regression. The results are given in Table 3.

Fig.6 shows the comparison between the calculated results from MA model and the test results. It can be seen that the flow stress determined by the above method is in good agreement with the test data under most conditions. While under some deformation conditions, the calculated results are quite different from the actual data.

2.4 Johnson Cook (JC) model

The JC model is expressed as[11,12]:

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}) \tag{12}$$

where, σ is flow stress (MPa), ε is the true strain, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless parameter, $\dot{\varepsilon}$ and $\dot{\varepsilon}_0$ are the strain rate (s^{-1}) and the reference strain rate (s^{-1}), respectively. A, B, C, n

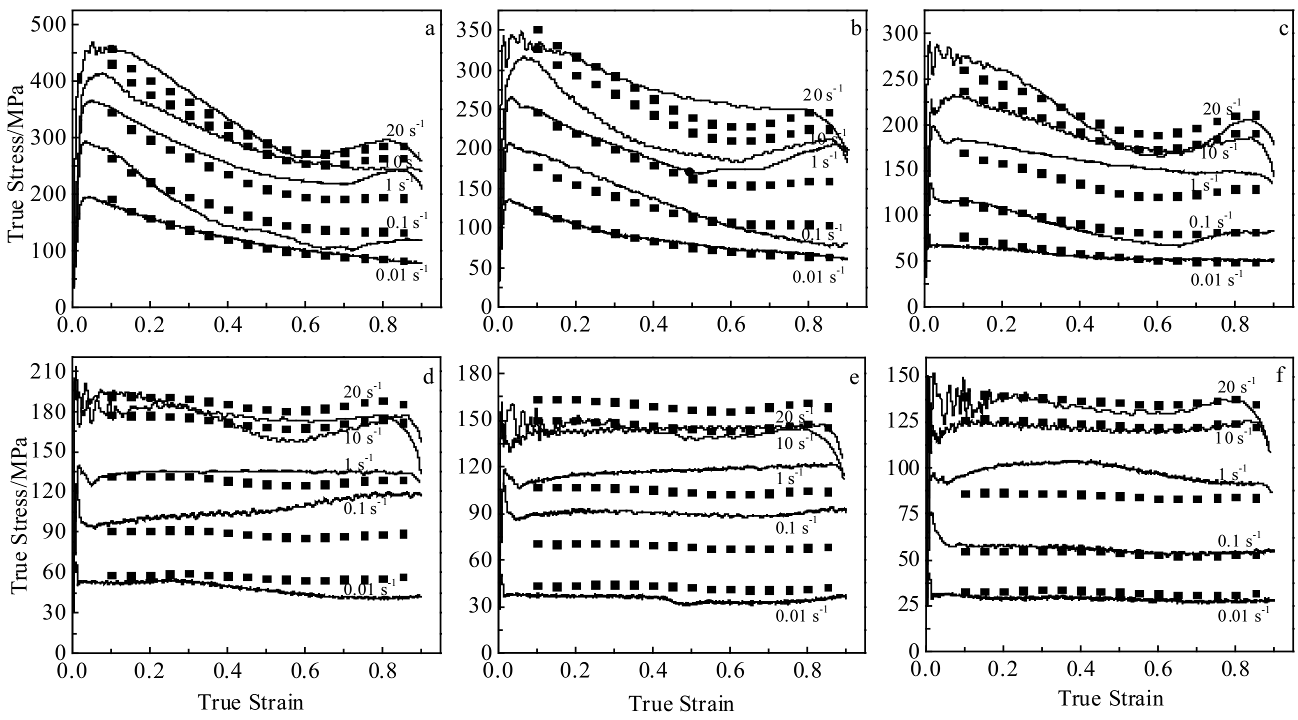

Fig.5 Comparison between the experimental and predicted flow stress from Eq. (1) at the temperatures of 1073 K (a), 1123 K (b), 1153 K (c), 1223 K (d), 1298 K (e), and 1373 K (f)

Table 3 Constants of TC17 titanium alloy in Eq. (11)

Phase	B_0	B_1	B_2	B_3
$\alpha+\beta$	–25.2844	7.679	0	–0.2553
β	–7.056	3.762	0.003535	–0.0264

and m are the material parameters. T^* is the contrast temperature and expressed as follows:

$$T^* = \frac{T - T_{\text{ref}}}{T_{\text{m}} - T_{\text{ref}}} \quad (13)$$

where, T is the deformation temperature (K), T_{m} is the melting temperature (1913 K for TC17 titanium alloy) and T_{ref} is the reference deformation temperature ($T \geq T_{\text{ref}}$). The JC model of as-cast TC17 titanium alloy is as follows:

$\alpha+\beta$ phase:

$$\sigma = (90.06 + 121.78\varepsilon^{-0.3485})(1 + 0.01387\ln\dot{\varepsilon}^*)(1 - T^{*0.6628}) \quad (14)$$

β phase:

$$\sigma = (51.77 + 83.535\varepsilon^{0.00691})(1 + 0.12355\ln\dot{\varepsilon}^*)(1 - T^{*1.049}) \quad (15)$$

Fig.7 shows the comparison of the flow stress obtained from JC model with the test results. It can be seen that the calculation results are in good agreement with the test results only at 1073 and 1223 K, but at other deformation temperatures, the calculation results show great difference with the actual data.

2.5 Modified Johnson Cook (MJC) model

The original JC model shows great errors, so the modified Johnson Cook (MJC) model has been proposed as[13]:

$$\sigma = (A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C\ln\dot{\varepsilon}^*)\exp[(\lambda_1 + \lambda_2\ln\dot{\varepsilon}^*)T^*] \quad (16)$$

In the equation, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the same as the original JC model, $T^* = T - T_{\text{ref}}$ with T and T_{ref} being the current and reference temperatures (K), respectively. A_1, B_1, B_2, C, λ_1 and λ_2 are the materials constants.

The MJC model of as-cast TC17 titanium alloy is:

$\alpha+\beta$ phase:

$$\sigma = (410.18 - 567.35\varepsilon + 432.87\varepsilon^2)(1 + 0.10998\ln\dot{\varepsilon}^*)\cdot \exp[(-0.00651 + 0.0004361\ln\dot{\varepsilon}^*)T^*] \quad (17)$$

β phase:

$$\sigma = (132.238 + 13.035\varepsilon - 13.051\varepsilon^2)(1 + 0.12356\ln\dot{\varepsilon}^*)\cdot \exp[(-0.00272 + 0.0002427\ln\dot{\varepsilon}^*)T^*] \quad (18)$$

Fig.8 shows a comparison of the flow stress obtained from the MJC model with the test results. It can be seen that the flow stress determined by the above method is in good agreement with the test data. Under the condition of partial deformation, there are obvious differences between the calculation results and the actual data.

3 Discussion

In order to evaluate the consistence between constitutive equation and test data more accurately, correlation coefficient R and average relative error (AARE) are used for further analysis, and the expression is[14]:

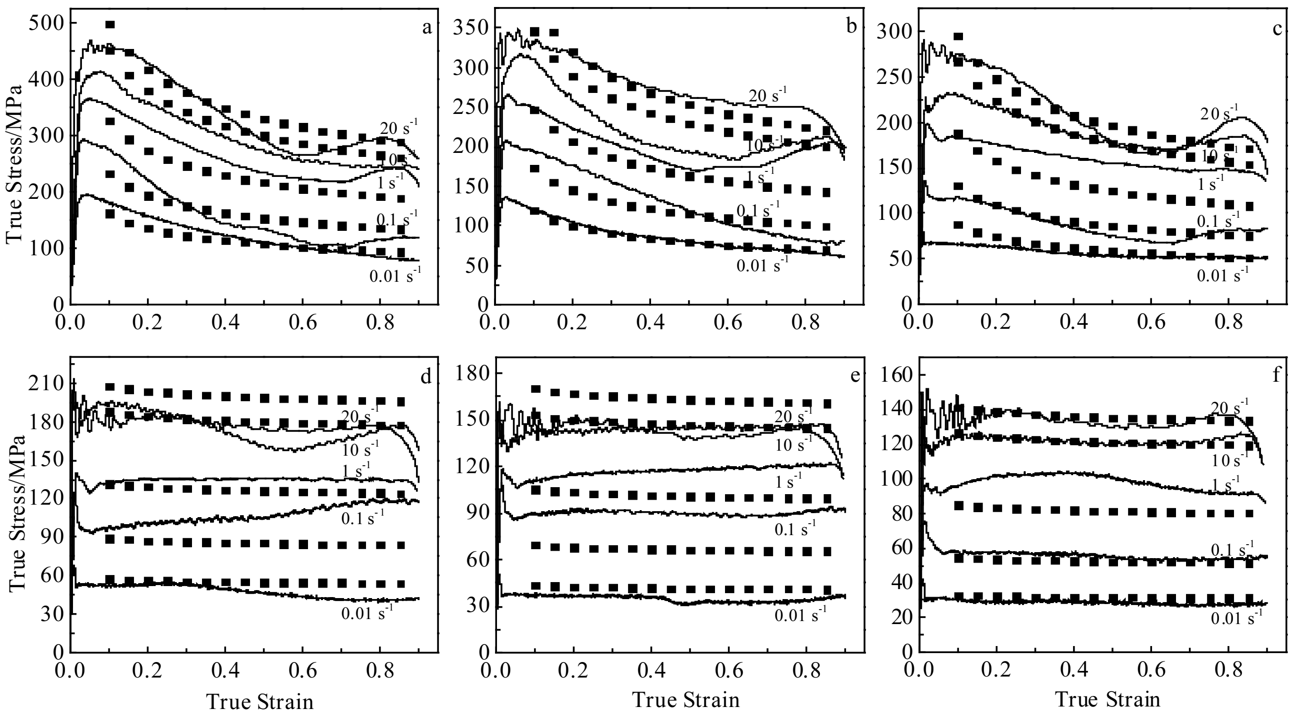

Fig.6 Comparison between the experimental and predicted flow stress for Eq. (11) at the temperatures of 1073 K (a), 1123 K (b), 1153 K (c), 1223 K (d), 1298 K (e), and 1373 K (f)

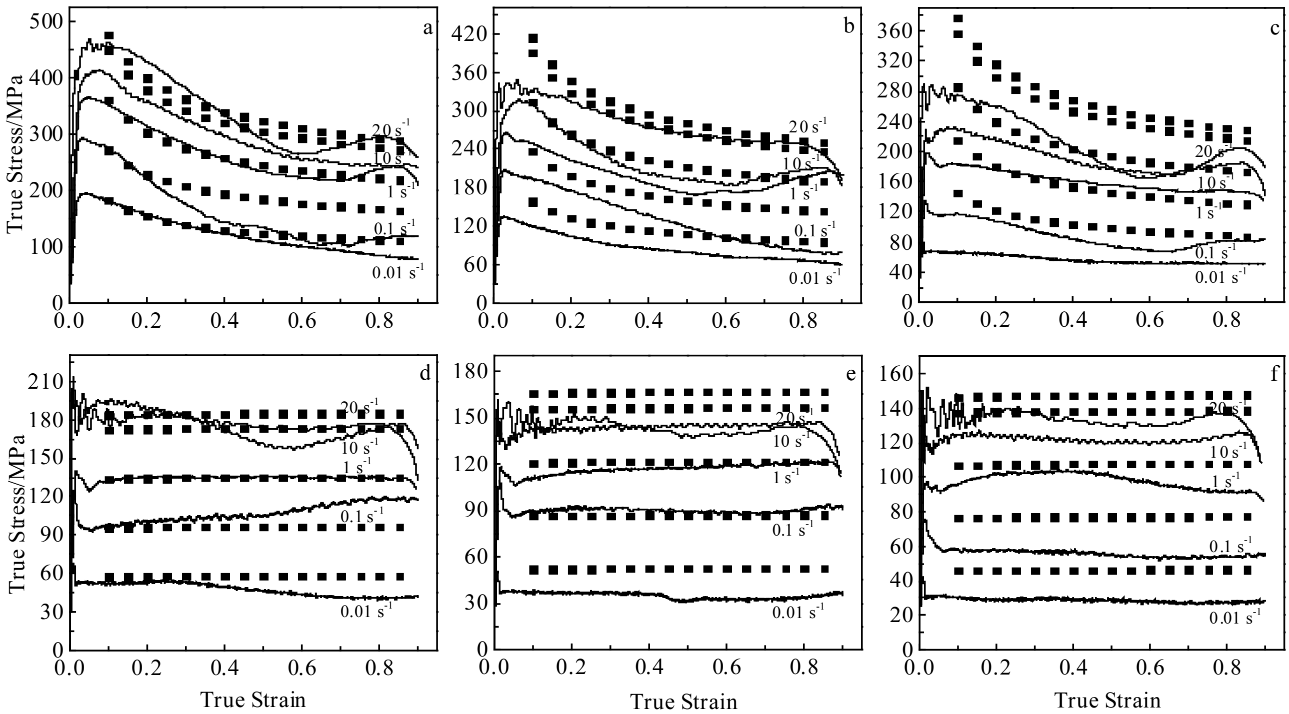

Fig.7 Comparison between the experimental and predicted flow stress for JC model at the temperatures of 1073 K (a), 1123 K (b), 1153 K (c), 1223 K (d), 1298 K (e), and 1373 K (f)

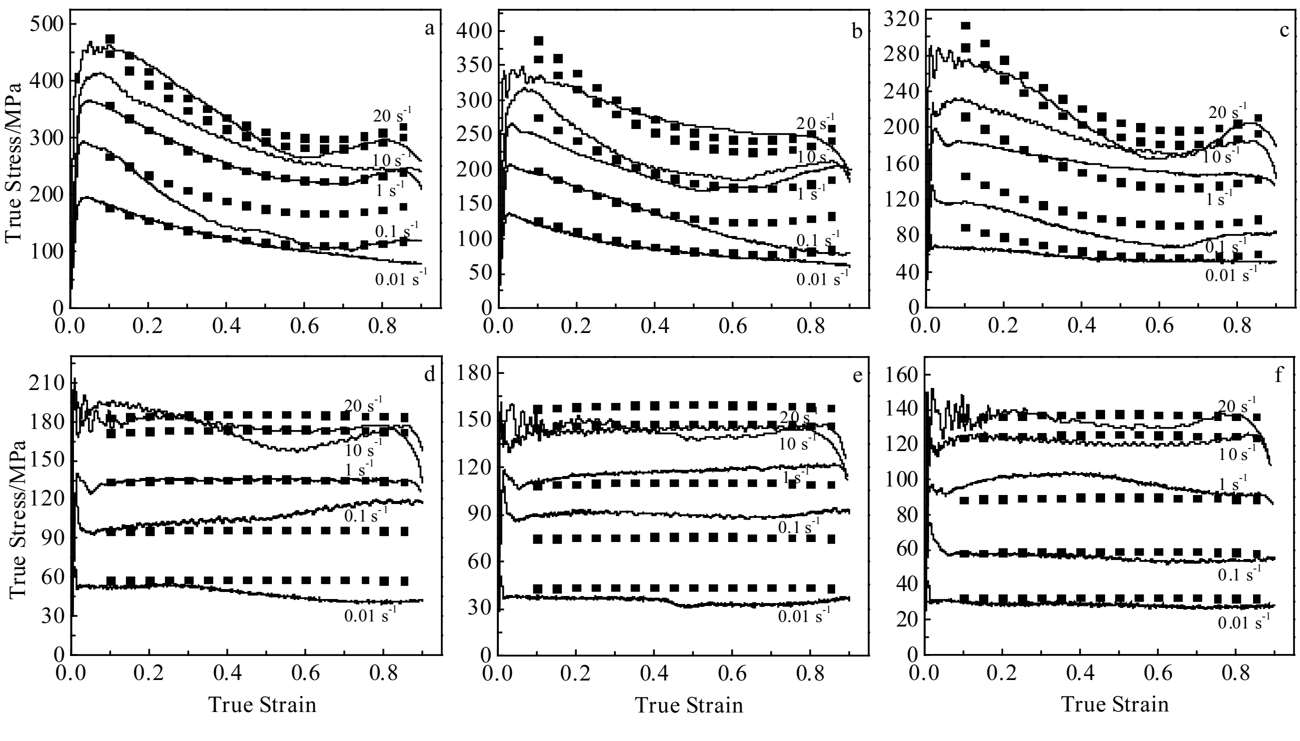

Fig.8 Comparison between the experimental and predicted flow stress for MJC model at the temperatures of 1073 K (a), 1123 K (b), 1153 K (c), 1223 K (d), 1298 K (e), and 1373 K (f)

$$R = \frac{\sum_{i=1}^{N}(E_i - \overline{E})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{N}(E_i - \overline{E})^2 \sum_{i=1}^{N}(P_i - \overline{P})^2}} \tag{19}$$

$$\text{AARE} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{E_i - P_i}{E_i}\right| \times 100\% \tag{20}$$

where, E_i is the test stress value (MPa); $\overline{E}$ is the average value of test stress (MPa); P_i is the calculated stress value (MPa); $\overline{P}$ is the calculated average value of flow stress (MPa); N is the number of collected data. Fig.9 shows the comparison between tested data and predicted data by the four constitutive models. As shown in Fig.9, the values of R for SCA, MA, JC and MJC models are 0.984, 0.975, 0.956 and 0.981, respectively. The AARE-values of SCA, MA, JC and MJC models are 8.962%, 10.84%, 23.93% and 10.75%, respectively.

Meanwhile, the values of AARE and R in the α+β phase and single β phase are compared in Fig.10. It can be seen from Fig.10a that, in α+β phase, the AARE value of SCA model is the lowest (7.601%), followed by MA (10.02%), MJC (12.53%) and JC (30.42%). In addition, the R values of SCA, MA, JC and MJC models are 0.981, 0.970, 0.952 and 0.977. Therefore, SCA model exhibits the highest accuracy in α+β phase. It should be noted that the AARE values of JC model are 30.42% and 17.43% for α+β phase and single β phase, respectively, which indicate that JC model is not suitable for describing the high temperature flow stress of as-cast TC17 titanium alloy. For the single β phase, the AARE-values are 10.32% (SCA model), 11.66% (MA model) and 9.332% (MJC model). The R-values are 0.973 (SCA model), 0.963 (MA model) and 0.981 (MJC model). Therefore, MJC model shows more accuracy than other models in single β phase.

In order to further analyze the effectiveness of each constitutive model, the relative error is used to analyze the effectiveness of the constitutive model:

$$\text{Relative error} = \left(\frac{E_i - P_i}{E_i}\right) \times 100\% \tag{21}$$

Due to the large error of JC model, only SCA, MA and MJC models are analyzed. Fig.11 shows the relative error comparison of different constitutive models. It can be seen that most of the relative errors of SCA (Fig.11a) and MJC (Fig.11c) models are in the range from –10% to 10%, while the relative errors of MA model are relatively scattered. For SCA model, there are 202 relative error data located between –5% and 5%, MA model is 139, and MJC model is 182, indicating that SCA model has the most accurate data, MJC model is the second, and MA model is the least. However, there are 54 (SCA), 60 (MA) and 73 (MJC) relative errors being higher than 20%. In addition, the relative error range of SCA model is –38.306%~25.197%, with an average of –0.00627; the relative error range of MA model is –38.091%~30.353%, with

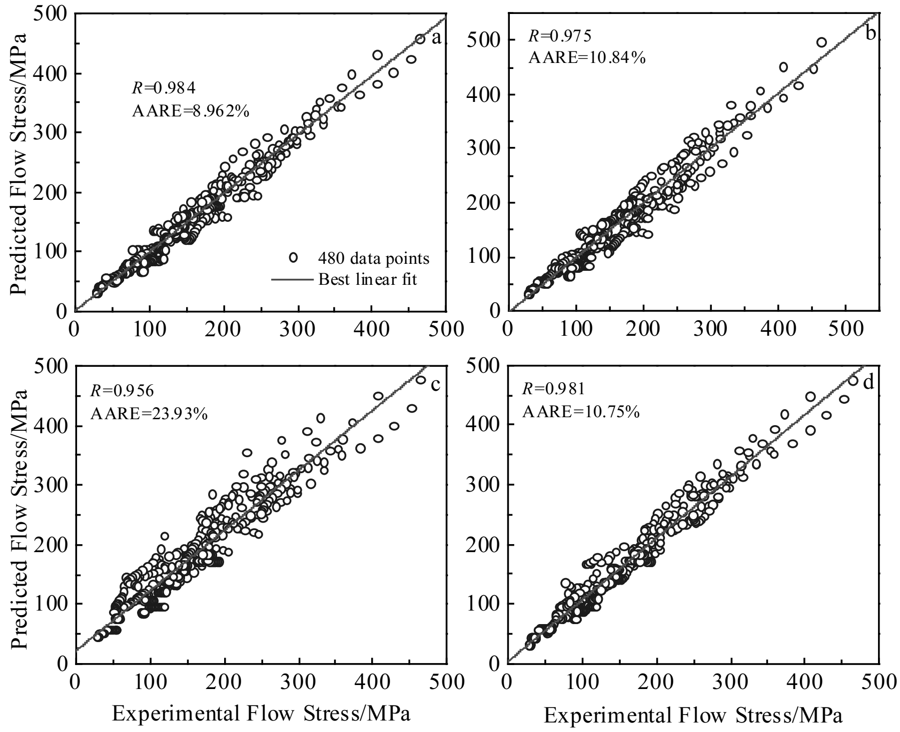

Fig.9 Correlation between the predicted and experimental flow stress data from the developed constitutive equations: (a) SCA model, (b) MA model, (c) JC model, and (d) MJC model

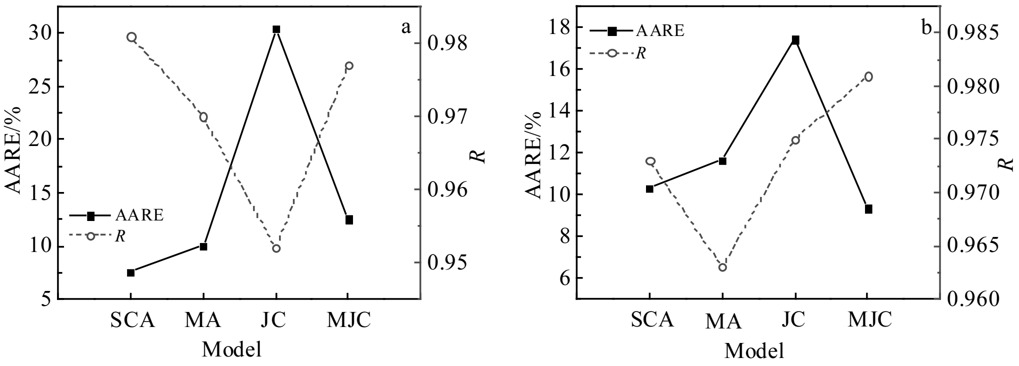

Fig.10 Correlation of AARE and R for different constitutive models in $\alpha+\beta$ phase (a) and single β phase (b)

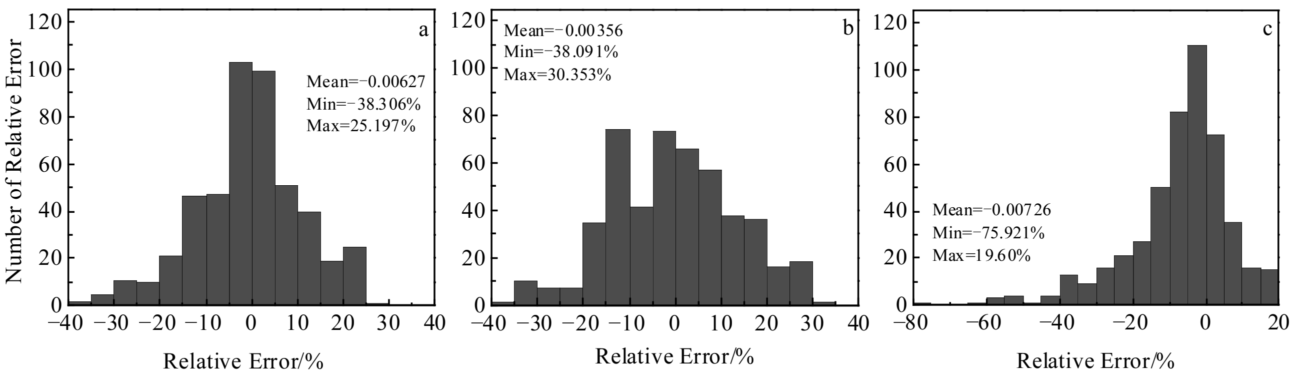

Fig.11 Correlation of values of relative error for different constitutive models: (a) SCA model, (b) MA model, and (c) MJC model

an average of –0.00356; the relative error range of MJC model is –75.921%~19.60%, with an average of –0.00726. Therefore, in the whole deformation temperature range, the SCA model proposes can more accurately conform to the high-temperature rheological curve of as-cast TC17 titanium alloy.

4 Conclusions

1) The SCA, MA, JC and MJC models are established to predict the flow stress of as-cast TC17 titanium alloy.

2) JC model can not accurately describe the high temperature flow behavior of as-cast TC17 titanium alloy. In the $\alpha+\beta$ two-phase region, the accuracy of the SCA model is the highest, while in the β single-phase region, the accuracy of the MJC model is the highest.

3) According to AARE, R and relative error analysis, the SCA model can more accurately conform to the high temperature rheological curve of as-cast TC17 titanium alloy in the whole deformation temperature range.

References

1 Li J L, Zeng W D, Lai Y J *et al*. *Materials Science and Engineering A*[J], 2014, 597: 387

2 Li L, Li M Q. *Materials Science and Engineering A*[J], 2017, 698: 302

3 Matsumoto H, Naito D, Miyoshi K *et al*. *Science and Technology of Advanced Materials*[J], 2017, 18(1): 893

4 Tarín P, Fernández A L, Simón A G *et al*. *Materials Science and Engineering A*[J], 2006, 438-440: 364

5 Sasaki L, Hénaff G, Arzaghi M *et al*. *Materials Science and Engineering A*[J], 2017, 707: 253

6 Wang B L, Ai X, Liu Z Q *et al*. *Journal Wuhan University of Technology, Materials Science Edition*[J], 2015, 30(3): 611

7 Liu Q, Wang Y D, Zheng H *et al*. *Optics and Laser Technology*[J], 2016, 82: 1

8 Mandal S, Rakesh V, Sivaprasad P V *et al*. *Materials Science and Engineering A*[J], 2009, 500: 114

9 Cai J, Wang K S, Miao C P *et al*. *Materials and Design*[J], 2015, 65: 272

10 Li M Q, Pan H S, Lin Y Y *et al*. *Journal of Materials Processing Technology*[J], 2007, 183(1): 71

11 Abbasi-Ban A, Zarei-Hanzaki A, Pishbin M H *et al*. *Mechanics of Materials*[J], 2014, 71: 52

12 Cai J, Wang K S, Han Y Y. *High Temperature Materials and Processes*[J], 2016, 35(3): 297

13 Lin Y C, Chen X M, Liu G. *Materials Science and Engineering A*[J], 2010, 527(26): 6980

14 Cai J, Wang K S, Zhai P *et al*. *Journal of Materials Engineering and Performance*[J], 2015, 24(1): 32

铸态 TC17 钛合金流动应力预测

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摘 要：通过热模拟压缩试验对铸态 TC17 钛合金的高温变形行为进行了研究。温度范围 1073～1373 K，应变速率范围 0.01～20 s^{-1}。建立了 4 种本构模型，分别是应变补偿双曲正弦模型、修正 Arrhenius 模型、Johnson Cook 模型和修正 Johnson Cook 模型，用来表征铸态 TC17 钛合金的高温流动应力。采用相关系数、平均相对误差和相对误差统计分析了 4 种模型的准确性。结果表明：Johnson Cook 模型不能用来描述铸态 TC17 钛合金高温流动应力；在 $\alpha+\beta$ 两相区，应变补偿双曲正弦模型精度最高，而在 β 单相区修正 Johnson Cook 模型更为准确；在整个变形温度范围内，应变补偿双曲正弦模型比其他几种模型的准确性更高。

关键词：铸态 TC17 钛合金；本构模型；流动应力

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