R. W. WANG, H. Y. LONG, L. N. QI, Y. M. LI, H. C. JI, Z M CAI

ISSN 0543-5846
METABK 59(1) 13-17 (2020)
UDC – UDK 669.295.7.018:539.374/536.45:620.16:620.172:62.001.57=111

STUDY ON ARRHENIUS MODEL OF TC6 TITANIUM ALLOY

Received – Primljeno: 2019-04-26
Accepted – Prihvaćeno: 2019-07-25
Original Scientific Paper – Izvorni znanstveni rad

At the deformation temperature of 1 103-1 283 K, with strain rate of 0,01 – 10 s^{-1}, and total strain of 0,7, the deformation behavior of TC6 titanium alloy was studied. The Arrhenius constitutive model is established by using stress - strain data when the strains of TC6 titanium alloy are 0,05, 0,1, 0,2, 0,3, 0,4, 0,5, 0,55, 0,6, and the accuracy of the model was verified. The results show that: the flow stress of TC6 titanium alloy increases as the strain rate increases and decreases as the deformation temperature increases; under different strains, the correlation coefficient (R) between the experimental value and the predicted value is greater than 98 %, and the average relative error (AARE) is lower than 10 %, which suggests that the established model has a higher prediction.

Key words: TC6 titanium alloy; high temperature deformation; stress; strain; Arrhenius constitutive model.

INTRODUCTION

TC6 titanium alloy is a two-phase titanium alloy with relatively complicated microstructure, and it has advantages such as low density, good corrosion resistance, great specific stiffness and specific strength and so on. Besides, it also possesses good impact toughness and plastic properties; for this reason, it is widely used in industries such as aerospace, automobile and household appliances etc., and it is top choice for the manufacture of components of space shuttle [1 - 3].

In recent years, many scholars have done a lot of research on the Arrhenius constitutive equations with different materials. Samantaray et al. [4] established Arrhenius constitutive model of 9Cr - 1Mo steel, and used it to predict high temperature flow stress, and a good prediction results are obtained. He et al. [5] calculated the deformation activation energy of Fe – 36 % Ni Invar alloy and the basic parameters of Arrhenius constitutive model, the Arrhenius constitutive model was established. The accuracy of the model was obtained by calculating the average relative error and correlation coefficient.

Mosleh et al. [6] established an Arrhenius constitutive model suit for many kinds of titanium alloys, and the accuracy of the established model was verified. Yan et al. [7] established a new type of Arrhenius constitutive model based on the deformation temperature to predict the residual stress distribution of Ti - 6Al - 4V, and the surface residual stress of Ti - 6Al - 4V board was detected by using X-ray to verify the accuracy of the model. However, there are few studies on the constitutive equations of TC6. As an important alloy material in the industry of aerospace and automobile, it is necessary to study its constitutive relation.

In this paper, the Arrhenius constitutive model of it was studied based on the high temperature deformation test of TC6, and the parameters of Arrhenius constitutive model of TC6 were calculated with strains of 0,05, 0,1, 0,2, 0,3, 0,4, 0,5, 0,55 and 0,6. Its Arrhenius constitutive models were established under different strain conditions, and the accuracy of models was verified.

MATERIALS AND EXPERIMENTAL

The material adopted in the experiment was TC6 titanium alloy, and its chemical composition is shown in Table 1.

Table 1 **Chemical composition of TC6 /wt. %**

H	N	C	Si	Fe
≤ 0,015	≤ 0,05	≤ 0,1	0,15 - 0,4	0,2 - 0,7
Cr	Al	Mo	Ti	
0,8 - 2,3	5,5 - 7,0	2 - 3	Balance	

The experiment was carried out on Gleeble - 1 500D thermal simulated test machine, the deformation temperature was set as 1 103, 1 163, 1 223, 1 283 K, the strain rate was set as 0,01, 0,1, 1, 10 s^{-1}, and the total strain was set as 0,7. The sample was heated to the deformation temperature at a rate of 10 K / s, then kept it warm for 3 minutes, and then it would proceed with isothermal compression.

RESULTS AND DISCUSSION
STRESS - STRAIN CURVE

Figure 1 shows the true stress - true strain curves of TC6 titanium alloy. As shown in the figure, the true

R. W. Wang, H. Y. Long (E-mail:lhy@ncst.edu.cn), L. N. Qi, Y. M. Li, Z. M. Cai, College of Mechanical Engineering, North China University of Science and Technology, Hebei, Tangshan, China; H. C. Ji, College of Mechanical Engineering, North China University of Science and Technology, Hebei, Tangshan, China; National Center for Materials Service Safety, University of Science and Technology Beijing, China; School of Mechanical Engineering, University of Science and Technology Beijing, Beijing, China.

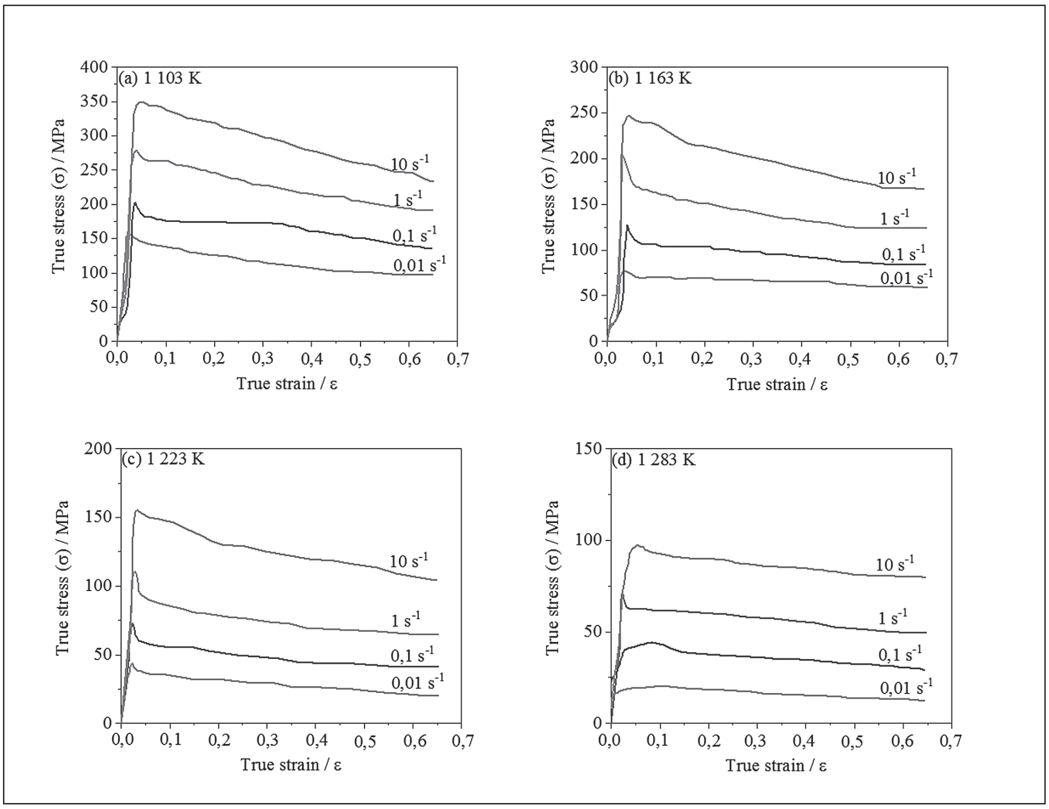

Figure 1 True stress - true strain curves of TC6 titanium alloy under different conditions: (a) 1 103 K; (b) 1 163 K; (c) 1 223 K; (d) 1 283 K.

stress - true strain curves under different conditions is consistent, that is, abrupt increases first, and then drops slowly after reaching the peak value, and finally gets stable; the values of flow stress will increases as the strain rate increases, and decreases as the deformation temperature increases; there is only a peak value of true stress - true strain curves, which indicates the main softening mechanism is dynamically recrystallized in the process of high temperature deformation of TC6 titanium alloy; the peak value of true stress - true strain curves decreases as the deformation temperature increases, and increases as the strain rate increases.

ESTABLISHMENT OF ARRHENIUS MODEL

The Arrhenius constitutive model was established by Sellers and Tegart [8 - 9], and it can be used to describe the relations between strain rate, deformation temperature and strain in the process of deformation of metal and alloy at high temperature. These three expression forms are often used for this model as below:

$$\dot{\varepsilon} = A\sigma^m \exp(-Q/RT) \quad (\alpha\sigma<0{,}8) \qquad (1)$$

$$\dot{\varepsilon} = B\exp(\beta\sigma)\exp(-Q/RT) \quad (\alpha\sigma>1{,}2) \qquad (2)$$

$$\dot{\varepsilon} = B\exp(\beta\sigma)\exp(-Q/RT) \quad (\text{For all } \sigma) \qquad (3)$$

α, β and m satisfies:

$$\alpha = \beta/\mathrm{m} \qquad (4)$$

In the equations: - strain rate / s^{-1}; A, B, C - material constant / s^{-1}; σ - true stress / MPa; R -constant of gas friction / 8,3 145·mol^{-1}·K^{-1}; Q - deformation activation energy / J·mol^{-1}; T - absolute temperature / K; m, n - stress exponent; α, β - parameters of stress level irrelevant to temperature.

In which, parameter Z can be introduced, which indicates the relations between deformation activation energy (Q), strain rate and deformation temperature in the process of deformation of metal.

$$Z = \dot{\varepsilon}\exp(Q/RT) \qquad (5)$$

Combining with equation (5):

$$\sigma = \frac{1}{\alpha}\ln\left\{\left(\frac{Z}{C}\right)^{\frac{1}{n}} + \left[\left(\frac{Z}{C}\right)^{\frac{2}{n}} + 1\right]^{\frac{1}{2}}\right\} \qquad (6)$$

Taking the stress under different deformation conditions when the strain is 0,3 as an example to calculate the material constant.

Taking the logarithms for equation (1) and equation (2):

$$\ln\dot{\varepsilon} = m\ln\sigma + \ln A - Q/RT \qquad (7)$$

$$\ln\dot{\varepsilon} = \beta\ln\sigma + \ln B - Q/RT \qquad (8)$$

The stress values at different deformation temperature (1 103, 1 163, 1 223, 1283 K) and different strain rates (0,01, 0,1, 1, 10 s^{-1}) were substituted into equation. (7) and equation. (8). The equation (7) and equation (8) were fitted to obtain the curves of - lnσ and - σ (As shown in Figure 2). As shown in equation (7) and equation (8), m and β refers to the slope of fitting curves. By calculation: m = 5,654, β = 0,065; the value of α can be obtained by equation (4): α = 0,0 115.

Taking the logarithms for equation (3):

$$\ln\dot{\varepsilon} = \ln C + n\ln[\sinh(\alpha\sigma)] - Q/RT \qquad (9)$$

As can be known from equation. (9). When deformation temperature and strain rate are definite, the following can be obtained:

$$n = \frac{\partial\ln\dot{\varepsilon}}{\partial\ln[\sinh(\alpha\sigma)]} \qquad (10)$$

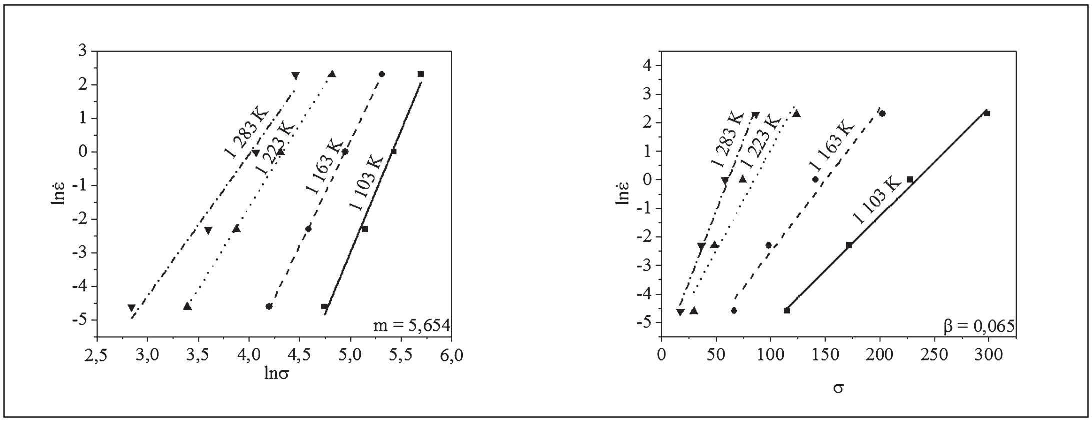

Figure 2 Relation curves of - lnσ and - σ.

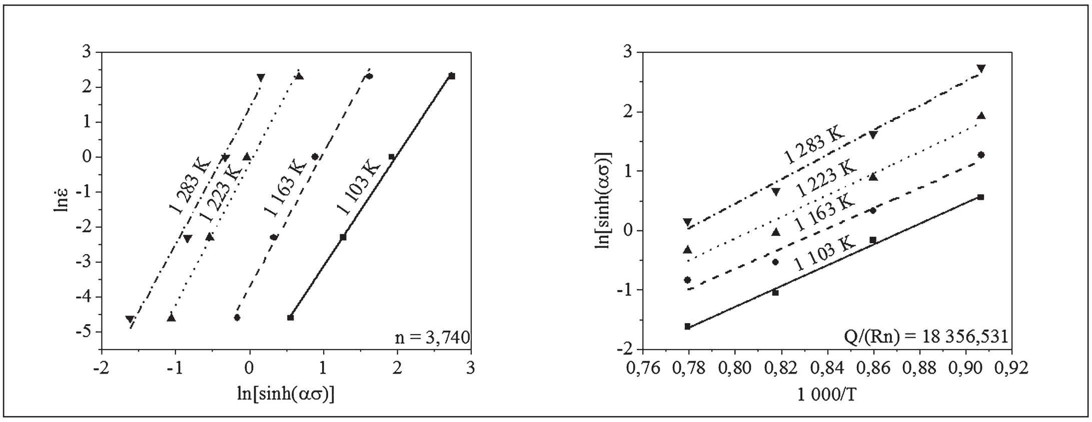

Figure 3 Relation curve of - ln[sinh($\alpha\sigma$)] and ln[sinh($\alpha\sigma$)] - 1 000/T.

$$Q/Rn = \frac{\partial \ln[\sin h(\alpha\sigma)]}{\partial(1/T)} \tag{11}$$

The above value α is substituted into equation (10) and (11), and equation (10) and (11) are fit under different conditions of deformation, and the fitting curves of ln$\dot{\varepsilon}$ - ln[sinh($\alpha\sigma$)] and ln[sinh($\alpha\sigma$)]- 1000/T are obtained respectively, as shown in Figure 3. From equation (10) and (11), n and Q/(Rn) are slopes of fitting curves, and the following can be obtained by calculation: n = 3,740, Q / (Rn) = 18 356,531.

Generally, R value is 8,3 145 $mol^{-1}\cdot K^{-1}$. By calculation, the deformation activation energy of TC6 can be obtained when the strain is 0,3: Q = 570,818 kJ/mol.

The Q was substituted into equation (5), and Z of different strain rate and deformation temperature can be obtained when the strain is 0,3. Taking equation (3) into equation (5), and taking the logarithm for both side of the equation:

$$\ln Z = \ln C + n \ln[\sin h(\alpha)] \tag{12}$$

From equation (12), it is known that ln$Z$ and ln[sinh($\alpha\sigma$)] are of linear relation, and ln$C$ is intercept of curve; ln$Z$ and ln[sinh($\alpha\sigma$)] are fit under different conditions of deformation, as shown in Figure 4. By calculation, the following results are obtained: ln$C$ = 55,457, $C = 1{,}215 \times 10^{24}$.

Taking A, C, n, Q into equation (6), and the Arrhenius constitutive model of TC6 titanium alloy can be obtained at the strain of 0,3:

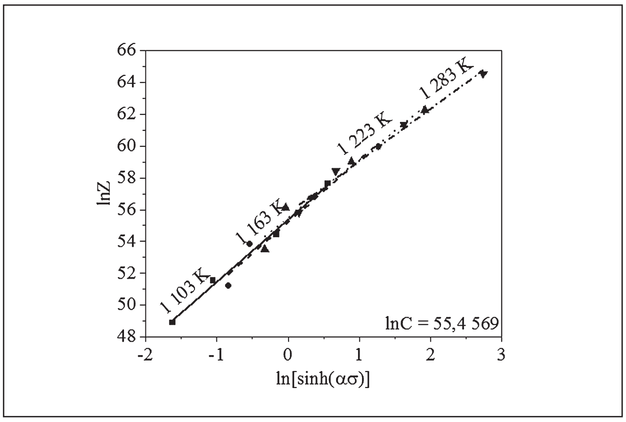

Figure 4 Relation curve of ln$Z$ and ln[sinh($\alpha\sigma$)] under different deformation temperatures.

$$\begin{cases} \sigma = \dfrac{1}{0{,}0115} ln \left\{ \left(\dfrac{Z}{1{,}215 \times 10^{24}} \right)^{\frac{1}{3{,}740}} + \left[\left(\dfrac{Z}{1{,}215 \times 10^{24}} \right)^{\frac{2}{3{,}740}} + 1 \right]^{\frac{1}{2}} \right\} \\ Z = \dot{\varepsilon} exp \dfrac{570818{,}35}{8{,}3145T} \end{cases} \tag{13}$$

Similarly, the values of m, β, α, n, Q and ln$C$ are obtained by using the above method when the strains

Table 2 **Values of *m*, *β*, *α*, *n*, *Q* and ln*C*.**

P	Strain			
	0,05	0,1	0,2	0,3
m	5,609	5,558	5,716	5,654
β	0,0 548	0,0 572	0,0 615	0,0 646
α	0,00 977	0,01 028	0,01,077	0,01 142
n	3,684	3,651	3,786	3,740
Q	568 399,05	557 498,79	584 208,57	570 818,88
ln*C*	55,1 601	54,1 329	56,8,748	55,4,569
P	Strain			
	0,4	0,5	0,55	0,6
m	5,494	5,529	5,517	5,519
β	0,0 657	0,0 699	0,0 711	0,0 722
α	0,01 197	0,01 265	0,01 288	0,01 309
n	3,647	3,676	3,674	3,683
Q	534 577,26	550 209,39	544 776,76	537 473,87
ln*C*	51,9 819	53,4 531	52,9 288	52,3 587

are 0,05, 0,1, 0,2, 0,4, 0,5, 0,55, 0,6. The results were shown as Table 2.

The Arrhenius constitutive model can be obtained by substituting the above parameter values into equation (6) when the strains of TC6 titanium alloy are 0,05, 0,1, 0,2, 0,4, 0,5, 0,55, 0,6.

Table 3 **R and AARE with different strains.**

Value	Strain			
	0,05	0,1	0,2	0,3
R	0,98 926	0,98 761	0,98 841	0,98 824
AARE / %	7,2 887	8,3 824	7,7 556	7,9 791
Value	Strain			
	0,4	0,5	0,55	0,6
R	0,98 447	0,99 024	0,98 977	0,98 783
AARE / %	8,7 262	7,9 878	8,0 226	8,6 204

VERIFICATION OF MODEL ACCURACY

In order to verify the accuracy of the established models, the correlation coefficient (R) and average relative error (AARE) are introduced, and the values of R and AARE can reflect the difference between the measured value and the predicted value significantly, and the expressions are as follows:

$$\text{AARE } /\% = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{E_i - P_i}{E_i}\right| \times 100\ \% \quad (14)$$

$$\text{R} = \frac{\sum_{i=1}^{N}(E_i - \overline{E})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{N}(E_i - \overline{E})^2 (P_i - \overline{P})^2}} \quad (15)$$

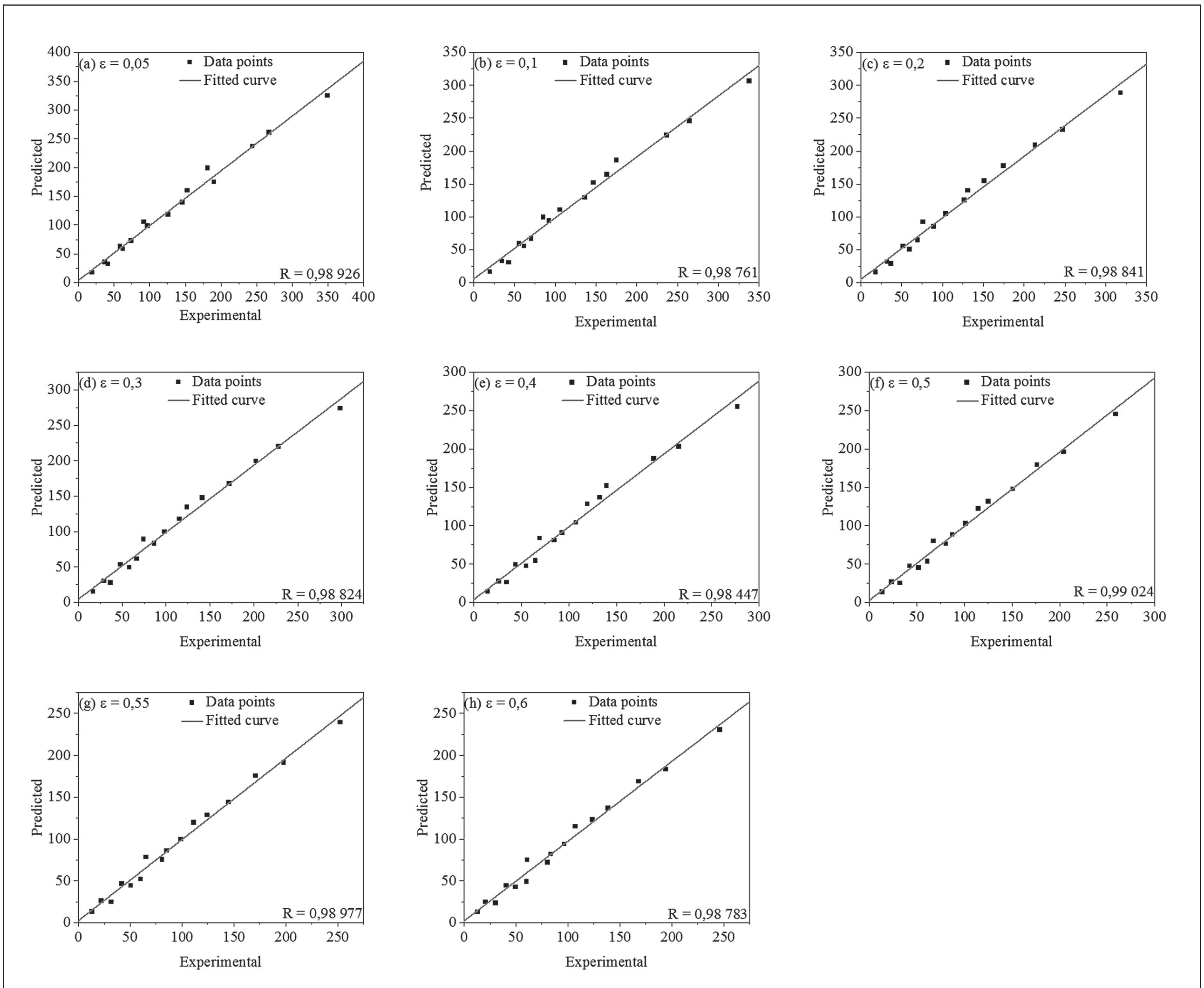

Figure 5 Comparison of the experimental value and the predicted value with different strains.

Where is: E - experimental stress / MPa; P - prediction stress / MPa; $\overline{E}, \overline{P}$ - average value of experimental stress and prediction stress / MPa.

Figure 5 shows comparison of the experimental value and the predicted value with the same strain, and values of R and AARE can be carried out under different strains by using equation (14) and equation (15). The results were shown in Table 3.

Through calculation and analysis, it is found that R is higher than 0,98 and values of AARE are lower than 10 % under different strains. which indicated that the established Arrhenius can well predicted the flow stress of TC6 titanium alloy in the process of deformation under the experimental conditions, and the establishment of the model provides certain referential values.

CONCLUSIONS

(1) Deformation temperature and strain rate have significant influence on the stress and strain curve of TC6 titanium alloy, and the values of flow stress will increase as the strain rate increases, and decreases as the deformation temperature increases.

(2) The Arrhenius constitutive models of TC6 titanium alloy were obtained at the strain of 0,05 - 0,6, and the accuracy of models was verified. The prediction meets the expected accuracy.

Acknowledgments

This work is supported by the North China University of Technology Doctoral Fund Launch Project (BS2017020). This work is also supported by the Scientific Research Fund of North China University of Science and Technology (Z201520).

REFERENCES

[1] M. Q. Li I, A. M. Xiong, W. C. Huang, H. R. Wang, S. B. Su, L. C. Shen. Microstructural evolution and modelling of the hot compression of a TC6 titanium alloy. Materials Characterization 49(2002)3, 203-209.

[2] C. H. Pei, Q. B. Fan, H. N. Cai, J. Z. Li. High temperature deformation behavior of the TC6 titanium alloy under the uniform DC electric field. Journal of Alloys & Compounds 489(2010)2, 401-407.

[3] J. Y. Xu, J. S. Liu, L. H. Bian. Establishement of Constitutive Relation of Hot Deformation TC6 Alloy. Journal of Shenyang Ligong University 33(2014)2, 17-20.

[4] D. Samantaray, S. Mandal, A. K. Bhaduri. A comparative study on Johnson Cook, modified Zerilli–Armstrong and Arrhenius-type constitutive models to predict elevated temperature flow behaviour in modified 9Cr-1Mo steel. Computational Materials Science 47(2009)2, 568-576.

[5] S. He, C. S. Li, Z. Y. Huang, J. J. Zheng. A modified constitutive model based on Arrhenius-type equation to predict the flow behavior of Fe-36%Ni Invar alloy. Journal of Materials Research 32(2017)20, 1-11.

[6] A. O. Mosleh, A. V. Mikhaylovskaya, A. D. Kotov, V. K. Portnoy. Arrhenius-Type Constitutive Equation Model of Superplastic Deformation Behaviour of Different Titanium Based Alloys. Defect & Diffusion Forum 385(2018), 45-52.

[7] G. X. Yan, A. Crivoi, Y. J. Sun, N. Maharjan, X. Song, F. Li, M. J. Tan. An Arrhenius equation-based model to predict the residual stress relief of post weld heat treatment of Ti-6Al-4V plate. Journal of Manufacturing Processes 32(2018), 763-772.

[8] Y. C. Lin, M. S. Chen, J. Zhang. Modeling of flow stress of 42CrMo steel under hot compression. Materials Science & Engineering: A (Structural Materials: Properties, Microstructure and Processing) 499(2009)1-2, 88-92.

[9] H. An, G. L. Xie, H. L. Zhang, X. T. Wang. A comparative study on Johnson-Cook, modified Johnson-Cook and Arrhenius-type constitutive models to predict the high temperature flow stress in 20CrMo alloy steel. Materials & Design 52(2013)24, 677-685.

Note: The responsible translator for English language is Y M Li-North China University of Science and Technology, China