ISSN 0543-5846
METABK 63(3-4) 419-422 (2024)
UDC – UDK 669.15.26.28.292.293.786:539.374-536.45:620.16-539.311/513.6:517.9=111

CONSTITUTIVE MODEL OF HIGH TEMPERATURE PLASTIC DEFORMATION OF P91 ALLOY STEEL

Received – Primljeno: 2023-12-21
Accepted – Prihvaćeno: 2024-02-22
Original Scientific Paper – Izvorni znanstveni rad

The hot compression test of as-cast P91 alloy steel was carried out by Gleeble3500 multi-functional thermal simulation test machine under the deformation conditions of temperature of 900 ~ 1 100 °Cand strain rate of 0, 1~5 s^{-1}. The high temperature flow behavior of as-cast P91 alloy steel was studied. The effects of strain rate and deformation temperature on the two-phase relationship of as-cast P91 alloy steel were analyzed. The strain rate compensation factor Z was introduced, and the Arrhenius constitutive model equation was established. The results show that the theoretical value of the peak stress calculated by the constitutive model is in good agreement with the experimental results, and the correlation is 96, 8 %, which verifies the feasibility of the model.

Keyword: P91 alloy steel; high temperature plastic deformation; stress-strain curves; constitutive equation; Arrhenius model

INTRODUCTION

In recent years, with the rapid development of large-scale critical thermal power units, nuclear power units, petrochemical, aerospace, shipbuilding and military industries, the demand for large-diameter thick-walled seamless tubes has been increasing. P91 heat-resistant alloy steel (10Cr9Mo1VNbN) has become an ideal steel for power station boilers because of its good process performance, high temperature strength and excellent oxidation resistance[1].

Wang et mastered the basic data of forged P91 heat-resistant alloy steel through thermal simulation experiments, and established a mathematical model of high temperature flow stress of forged P91 heat-resistant alloy steel[2]. However, there are few studies on the hot deformation behavior and microstructure evolution of as-cast P91 heat-resistant alloy steel. The as-cast structure is obviously different from the forged structure in hot deformation behavior and hot processing technology, and the microstructure evolution law is also different from the forged structure. Therefore, it is necessary to study the hot deformation behavior of the steel and establish the corresponding constitutive relation model[3].

In this paper, the high temperature compression experiment of P91 alloy steel was carried out by using Gleeble3500 multi-functional thermal simulator, and the variation characteristics of flow stress-strain curve were studied. The effects of temperature, strain rate and strain were included in the calculation, and the constitutive model, power dissipation diagram and thermal processing diagram under different strains were established. The experimental data were compared with the predicted data of the model to verify the accuracy of the constitutive model.

P91 alloy steel hot compression test

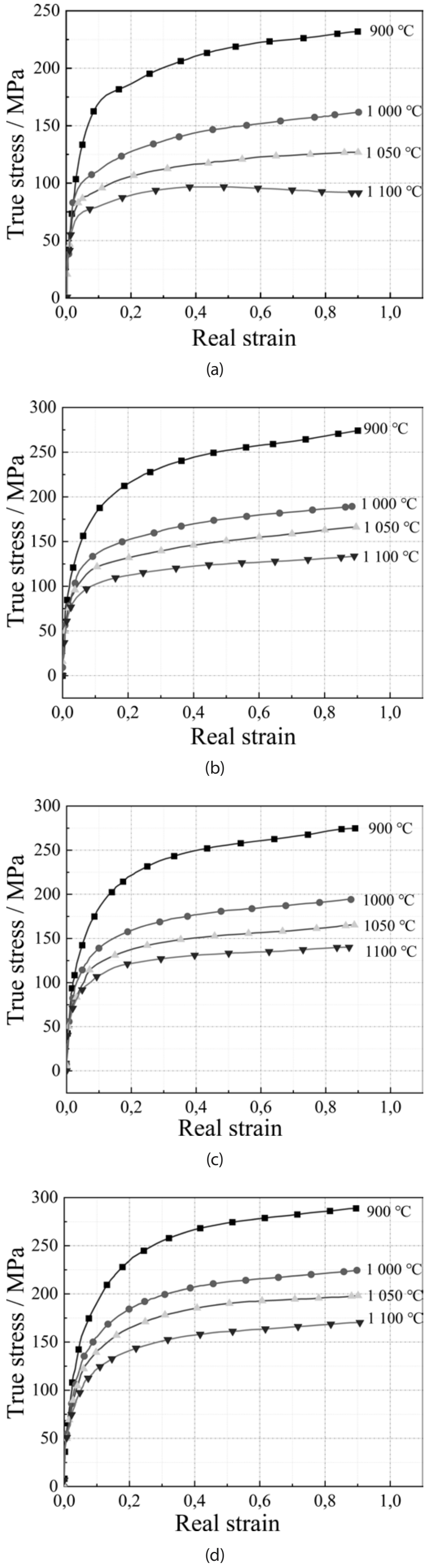
According to the requirements of thermal simulation experiments, the material was cut from the bottom of the as-cast P91 heat-resistant steel ingot and processed into a *Ø*8mm×12mm cylindrical sample. The samples were placed on the Gleeble-3500 thermal/mechanical simulator for compression test. The deformation temperature of the thermal simulation experiment was set at 900, 1 000, 1 050 and 1 100 °C, the strain rate was 0,1, 0,5, 1 and 5 s^{-1}, and the deformation was 60 %. After the compression was completed, the water quenching treatment was carried out to retain the high temperature deformation structure.

Experimental data and ontological modeling

The true stress-true strain curve of P91 alloy steel under the strain change rate of 0,1 ~ 5 s^{-1} is shown in Figure 1. In the process of hot deformation, on the one hand, the metal will produce work hardening, on the other hand, it will also produce dynamic softening, dynamic recovery and dynamic recrystallization. It can be seen from Figure 1 that at lower strain rate and higher deformation temperature, the flow stress rises sharply from the beginning to a certain peak and then tends to be stable, and the stress-strain curve shows a typical dynamic recovery type. This is because in the process of increasing deformation, the dynamic softening effect

---

P. Huo, X. Li, W. Li (E-mail: huop@ncst.edu.cn), North China University of Science and Technology, Hebei, Tangshan, China.



(a) 0, 1 s^{-1} (b) 0,5 s^{-1} (c) 1 s^{-1} (d) 5 s^{-1}

Figure 1 P91 alloy steel true stress-true strain curve

will gradually increase, and have a certain offset effect on work hardening, and finally achieve a balanced and stable state. With the increase of deformation temperature, the flow stress begins to decrease with the increase of strain after reaching a certain peak, and tends to be stable or wavy with the increase of strain.

In the process of decreasing deformation temperature and increasing strain rate, on the one hand, it will lead to the increase of flow stress, on the other hand, it will lead to the increase of steady-state strain, peak strain and the difference between them. With the increase of strain rate, the temperature range of dynamic recrystallization and dynamic recovery will be continuously reduced. The magnitude of temperature and strain rate has a significant effect on the peak and steady-state stress. When the deformation temperature is low and the strain rate is large, the hardening has been dominant in the whole deformation process, and no peak stress is generated. It can be seen from the figure that the material has obvious dynamic recrystallization behavior when the temperature is greater than 1 000 °C. When the strain rate is constant, the peak strain decreases ; when the temperature is constant, the peak strain increases with the increase of strain rate.

In order to explore the influence of processing parameters on the flow stress during the deformation of P91 alloy steel, an Arrhenius-type constitutive model was established to quantitatively describe the relationship between flow stress σ, temperature T and strain rate $\dot{\varepsilon}$. The temperature-compensated strain rate Zener-Hollomon parameter Z was introduced for strain rate compensation. The parameter is a temperature-independent function of flow stress and deformation degree. The relationship among flow stress σ, temperature T and strain rate $\dot{\varepsilon}$ during hot deformation at high temperature can be expressed as:

$$\dot{\varepsilon} = A_1 \sigma^{n_1} \exp(\frac{-Q}{RT}) \tag{1}$$

$$\dot{\varepsilon} = A_2 \exp(\beta\sigma) \exp(\frac{-Q}{RT}) \tag{2}$$

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

where $\dot{\varepsilon}$ is strain rate, s^{-1}; σ is stress, *MPa*; A, A_1, A_2, α, β, n and n_1 are temperature-independent material constants, and $\alpha = \beta / n_1$; T is the deformation temperature, K, R is the molar gas constant, the value is 8,314J (mol/K)$^{-1}$, and Q is the apparent activation energy (J/mol) of hot deformation.

$$In\dot{\varepsilon} + \frac{Q}{RT} = InA_1 + n_1 In\sigma \tag{4}$$

$$In\dot{\varepsilon} + \frac{Q}{RT} = InA_2 + \beta\sigma \tag{5}$$

$$\dot{\varepsilon} = A\left[\sinh(\alpha\sigma)\right]^n \exp(\frac{-Q}{RT}) \tag{6}$$

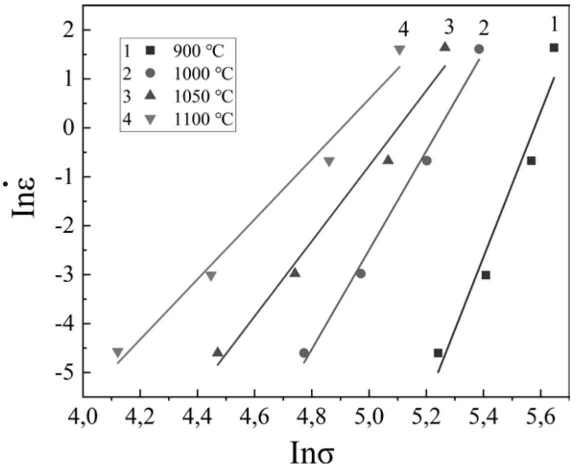


Figure 2 Relation curves of ln$\dot{\varepsilon}$ and ln σ

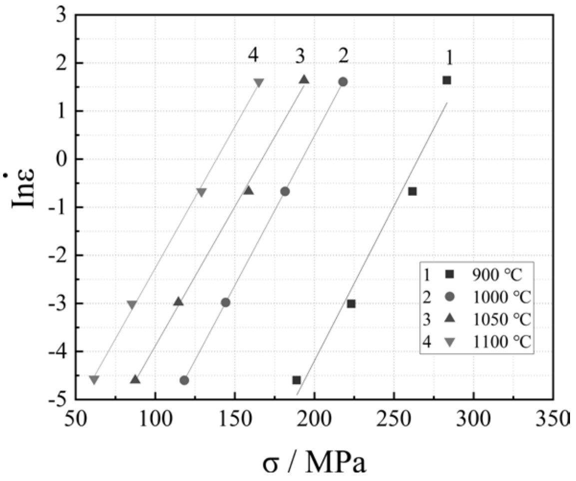


Figure 3 Relation curves of ln$\dot{\varepsilon}$ and σ

In the case of constant temperature, linear fitting is performed on $\ln\dot{\varepsilon}-\ln\sigma$ and $\ln\dot{\varepsilon}-\sigma$, as shown in Figure 2, 3.

n_1 = 9,69856 and β = 0,06084 can be obtained from the graph; according to the relation of $\alpha = \beta / n_1$, α = 0,006273 MPa^{-1} is obtained.

Substituting the above obtained data into Eqs. (4)~(6), the partial differential is obtained by simultaneous and partial differential:

$$Q = R\left\{\frac{\partial In\dot{\varepsilon}}{\partial In\left[\sinh\left(\alpha\sigma\right)\right]}\right\}_T\left\{\frac{\partial In\left[\sinh\left(\alpha\sigma\right)\right]}{\partial\left(1/T\right)}\right\}_{\dot{\varepsilon}} \qquad (7)$$

$$Q = Rnk \qquad (8)$$

The stress-strain data are substituted into Eq. (6), and the$\ln\dot{\varepsilon}-\ln\left[\sinh\left(\alpha\sigma\right)\right]$ and $\ln\left[\sinh\left(\alpha\sigma\right)\right]-1/T$ curves at different temperatures are fitted. As shown in Figure 4,5, the slope of the straight line in the figure is calculated and the average value is obtained. The obtained results are substituted into Eq. (8) to obtain the thermal deformation activation energy Q = 447,719 $kJ \cdot mol^{-1}$.

The effects of deformation temperature and strain rate on the flow stress of as-cast P91 alloy steel can be expressed by Zener-Hollomom parameter Z :

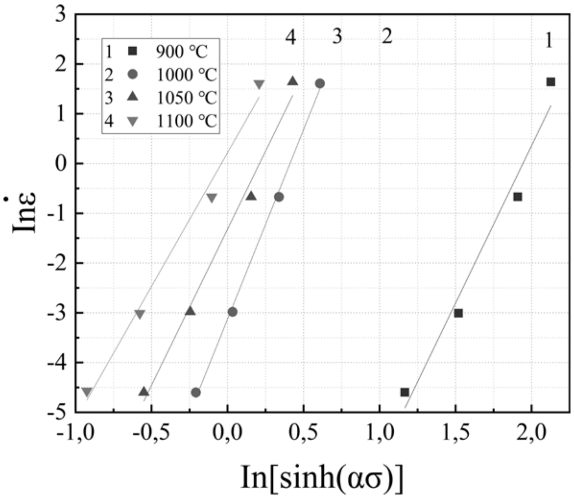


Figure 4 Relation curves of ln $\dot{\varepsilon}$ and ln[sinh(ασ)]

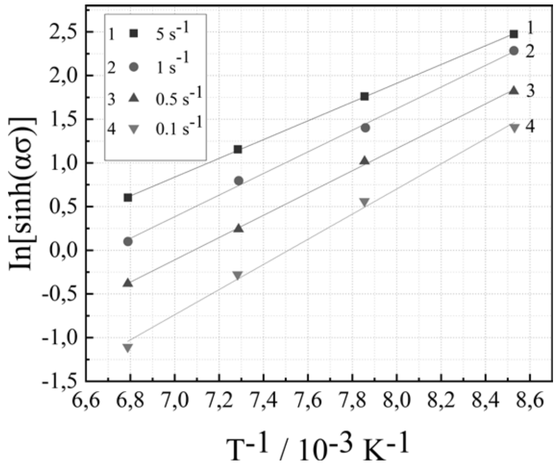


Figure 5 Relation curves of ln[sinh(ασ)] and 1 / T

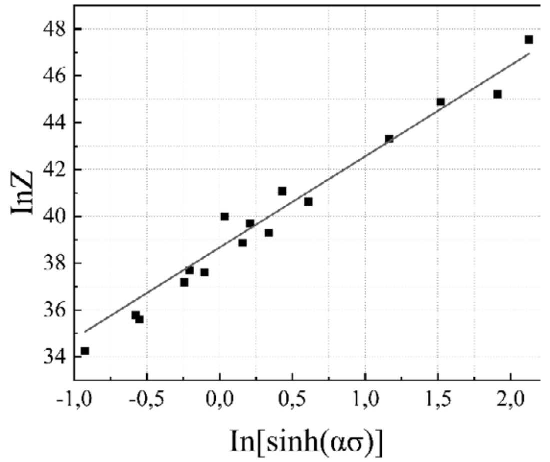


Figure 6 Relation curves of lnZ and ln[sinh(ασ)]

$$Z = \dot{\varepsilon}\exp\left[\frac{Q}{RT}\right] = A\left[\sinh\left(\alpha\sigma\right)\right]^n \qquad (9)$$

Logarithmize the two sides of the formula to get:

$$\ln Z = n\ln[\sinh(\alpha\sigma)] + \ln A \qquad (10)$$

It can be seen from Formula (10) that the slope of the straight line in Fig .6 is n and the intercept is ln A. Thus, n = 3,89099, ln A = 4,2393925.

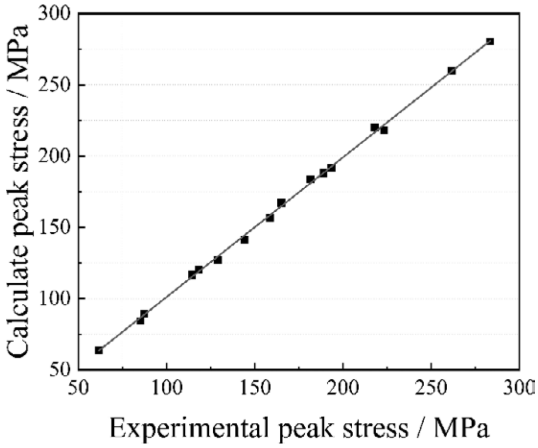


Figure 7 The peak stress calculation results are compared with the measured values

The calculated A, α, Q and n are brought into Formula (3) to obtain the peak stress constitutive equation of P91 alloy steel.

$$\dot{\varepsilon} = 6,23027 \times 10^{16} \left[\sinh(0.006273\sigma)\right]^{3,89099} \exp\left(\frac{-447\,719,1}{8,314T}\right) \quad (11)$$

Simulation prediction and verification of constitutive model

The experimental values and stress prediction values of P91 alloy steel at different temperatures and different strain rates are compared, as shown in Figure 7. The correlation coefficient between the calculated results of the constitutive model of P91 alloy steel and the experimental values is 0,968, the maximum relative error is 8,37 %, and the average relative error is 6,56 %. The established model can well predict the macroscopic stress of the material.

CONCLUSION

In this paper, the constitutive relationship of P91 alloy steel under different temperature and strain rate is studied. The Arrhenius constitutive model of P91 alloy steel was established, and the accuracy of the model in predicting flow stress was analyzed and verified. The results show that the constitutive model of P91 alloy steel established in this paper has certain accuracy, which provides a strong basis and reference for the study of plastic deformation of as-cast P91 alloy steel.

REFERENCES

[1] Subbiah R, Rahel M, Sravika A, et al. Investigation on microstructure and mechanical properties of P91 alloy steel treated with normalizing process-a review[J]. Materials Today, Proceedings, 2019, 18: 2265-2269

[2] G Runzhe, L Bufang, Z Xiangyu, etc. Modified constitutive model and deformation activation energy evolution of as-cast P91 alloy steel [J]. Journal of Plastic Engineering, 28 (2021) 04 , 181-189.

[3] Wen Chao, Sun Qianjiang, Xu Hao, etc. Flow stress prediction of TC21 titanium alloy based on Arrhenius model and modified Johnson-Cook model [J].According to Chinese Journal of Plastic Engineering, 11 (2023) 30 ,82-90.

Note: The responsible translator for English language is L. LI-North China University of Science and Technology, China