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ISSN 0543-5846
METABK 59(1) 63-66 (2020)
UDC – UDK 669.15.26.28:621.831:62.001.57:513.6-620.16/539.374=111

THE ARRHENIUS CONSTITUTIVE MODEL OF STEEL 42CrMo FOR GEAR

Received – Primljeno: 2019-07-16
Accepted – Prihvaćeno: 2019-09-10
Original Scientific Paper – Izvorni znanstveni rad

Thermal compression test temperature ranged from 800 to 1 200 °C, the strain rate ranged from 0,01 to 10 s^{-1}, and the deformation degree was 60 % of engineering strain, the deformation behavior of 42CrMo gear steel was studied. As the deformation temperature increases and the strain rate decreases, the stress decreases significantly. By polynomial fitting the relationship between strain(0,05 – 0,9, at intervals of 0,05) and material constants, the strain-compensationed Arrhenius constitutive equation for 42CrMo gear steel is established. The correlation coefficient between the experimental data and the predicted data reached 0,9925. This shows that the Arhenius constitutive equation has high accuracy in predicting steel 42CrMo for gear.

Key words: 42CrMo, gear, Arrhenius constitutive model, stress-strain curves, thermal deformation behavior

INTRODUCTION

The experimental research material is derived from the steel material of the conjunction gear [1] in the gearbox of a certain automobile - 42CrMo steel. Steel 42CrMo for gear (approximately US grade AISI-4140) has good strength, toughness and wear resistance and is widely used in various parts, including automotive crankshafts, plungers, shafts and conjunction gears in automotive transmissions.

The thermal compression test is an important experiment to study the deformation of metal shape, and a large number of accurate and realistic experimental data can be obtained. The experimental data have important theoretical significance for studying the thermal processing behavior of 42CrMo.

Sellars and Tegart [2] proposed the Arrhenius hyperbolic sinusoidal function model, which correctly reflects the relationship between flow stress, strain rate and deformation temperature.

EXPERIMENT

In order to study the thermal deformation behavior of 42CrMo gear steel, the Gleeble 1 500D thermomechanical simulator was used for thermal compression at temperatures of 800 °C, 900 °C, 1 000 °C and 1 200 °C with strain rates of 0,01, 0,1, 1 and 10 s^{-1}. The experimental sample is mm, and the sample is heated to the deformation temperature at a rate of 10 °C/s. After 3 minutes of heat preservation, the sample is isothermally compressed, and immediately quenched and quenched to maintain the microstructure state at high temperature deformation.

The flow stress and strain curve of 42CrMo gear steel is shown in Figure 1. The main components of 42CrMo gear steel billet are shown in Table 1.

Table 1 **Chemical composition of 42CrMo /wt. %**

C	Cr	Mn	Mo	Si
0,38 - 0,45	0,90 - 1,20	0,38 - 0,45	0,90 - 1,20	0,38 - 0,45
Ni	S	p	Fe	
≤ 0,30	≤ 0,035	≤ 0,035	Balance	

ESTABLISHMENT OF ARRHENIUS MODEL

Many studies have shown that the high temperature flow stress of metallic materials is related to deformation temperature, strain rate and composition of materials [3]. When the chemical composition in the metal material is fixed, the relationship between $\dot{\varepsilon}$ and σ can be expressed by a hyperbolic sine function.

$$\dot{\varepsilon} = f(\sigma)\exp\left(-Q/RT\right) \tag{1}$$

There are different equations at different pressure levels.

1) At low stress levels (ασ<0,8):

$$\dot{\varepsilon} = A_1\sigma^{n'}\exp\left(-Q/RT\right) \tag{2}$$

2) At high stress levels (ασ > 1,2):

$$\dot{\varepsilon} = A_2(\beta\sigma)\exp\left(-Q/RT\right) \tag{3}$$

3) Equation (1) can be reduced to hyperbolic sine at full stress level:

$$\dot{\varepsilon} = A[sinh(\sigma)\exp\left(-Q/RT\right) \tag{4}$$

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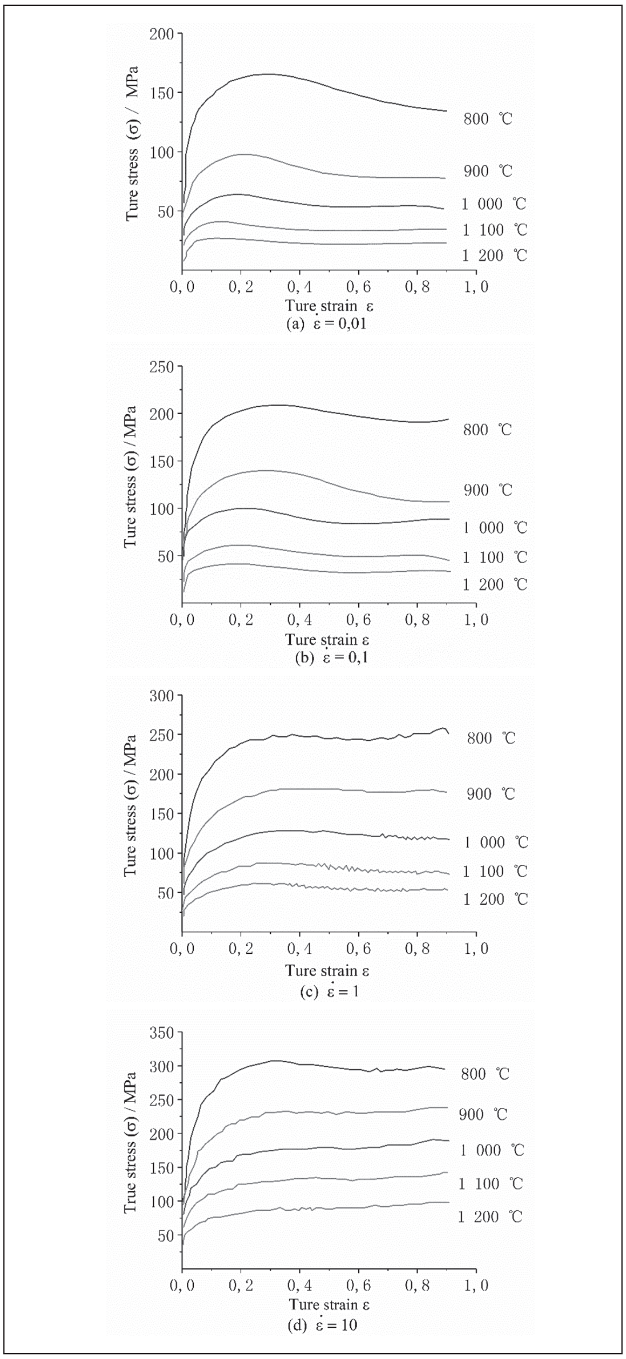

Figure 1 Flow stress-strain curves of 42CrMo

In these equations, $\dot{\varepsilon}$ is the strain rate; A, A_1, A_2 are material constants; α is the stress factor (α = β/n'), σ is the flow stress; n' is the stress index; Q is the thermal deformation activation energy; R is the molar gas constant, R = 8,314 J / (mol · K); T is the absolute temperature / K.

The relationship between $\ln\sigma_p - \ln\dot{\varepsilon}$ and $\sigma_p - \ln\dot{\varepsilon}$ is drawn by Origin, as shown in Figure 2(a) and 2(b). The inverse values of the slopes are determined separately. The average is available: n' = 7,227. Similarly, β = 0,065. According to (α = β/n'), α = 0,009 is obtained. Take the logarithm of Equation (4):

$$\ln\dot{\varepsilon} = \ln C + n\ln[\sinh(\alpha\sigma)] - (Q/RT) \tag{5}$$

When the temperature T is constant, a certain linear relationship is exhibited:

$$n = \frac{\partial \ln\dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]} \tag{6}$$

There is a linear relationship between ln[sinh(as)] and 1/T when the strain rate is constant.

$$Q / Rn = \frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial(1/T)} \tag{7}$$

From Figure 2, these data can be obtained: n = 5,245, Q = 366 104,881 J/mol.The relationship between stress, strain rate and deformation temperature is described using the Zener-Hollomon parameter [4] as follows:

$$Z = \dot{\varepsilon}\exp(Q / RT) \tag{8}$$

Simultaneous Equation (4) and Equation (8):

$$\dot{\varepsilon} = 4{,}171\times10^{14}\left[0{,}009\sinh\left(\sigma_p\right)\right]^{5{,}245} \tag{9}$$

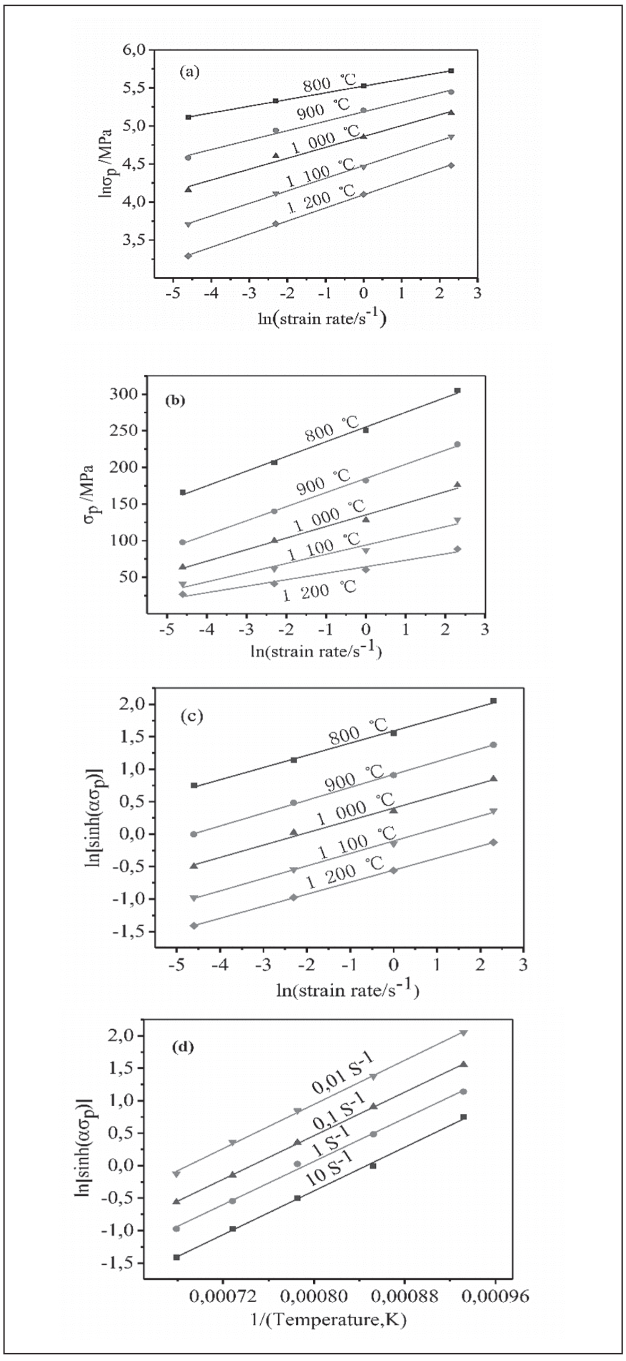

Figure 2 Relationships between (a) and ; (b) and ; (c) and ; (d) and 1/T;

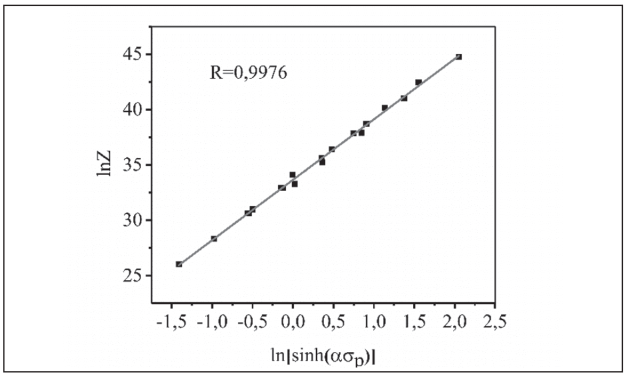

Figure 3 Relation relationship between and Verify the constitutive equation with strain compensation

According to the relationship of lnZ - ln[$sinh(\alpha\sigma^p)$], linear regression is performed, and Figure 3 can be obtained. According to the fitting curve, the intercept A = 4,171 × 1 0[14] can be obtained. According to the data in Figure 3, the correlation coefficient (R) can reach 0,9976. When 42CrMo steel is deformed at high temperatures, the relationship between peak stress and process parameters can be described by Equation (10):

$$\exp\left(-\frac{366\,104{,}881}{8{,}314T}\right) \tag{10}$$

Studies have shown that the thermal deformation activation energy and material constant of the material are affected by the strain over the entire strain range [5]. The strain factor is introduced into the Arrhenius equation to improve the accuracy of the equation prediction.

Table 2 **Values of α, n, Q / kJ/mol and lnA**

P	Strain					
	0,05	0,1	0,15	0,2	0,25	0,3
α	0,0116	0,0100	0,0092	0,0090	0,0091	0,0 092
n	7,103	6,486	5,973	5,554	5,196	4,959
Q	496,92	452,49	423,99	391,12	384,44	373,82
lnA	45,438	41,180	38,577	35,323	34,574	33,787
P	Strain					
	0,35	0,4	0,45	0,5	0,55	0,6
α	0,0093	0,0094	0,0095	0,0095	0,0095	0,0095
n	4,703	4,575	4,493	4,412	4,415	4,396
Q	360,65	348,27	349,56	342,37	339,62	336,61
lnA	32,282	31,155	31,343	30,723	30,532	30,279
P	Strain					
	0,65	0,7	0,75	0,8	0,85	0,9
α	0,0095	0,0095	0,0094	0,0093	0,0093	0,0094
n	4,408	4,391	4,410	4,418	4,432	4,377
Q	335,88	332,41	330,14	330,14	329,22	327,49
lnA	30,284	29,991	29,820	29,871	29,800	29,635

Table 3 **Coefficients of the polynomial for α, n, Q, and, ln A for 42CrMo gear steel.**

Coefficient	α	n	Q	lnA
K0	0,01489	7,79256	561,1626	51,42045
K1	-0,08696	-14,70417	-1 516,941	-140,9257
K2	0,4916	16,06924	5 297,060	479,76993
K3	-1,3699	13,73432	-11 540,23	-1 039,666
K4	2,05108	-42,16835	15 086,998	1 384,798
K5	-1,58351	33,35417	-10 653,27	-1 006,078
K6	0,49403	-9,8444	3 097,47	300,87176

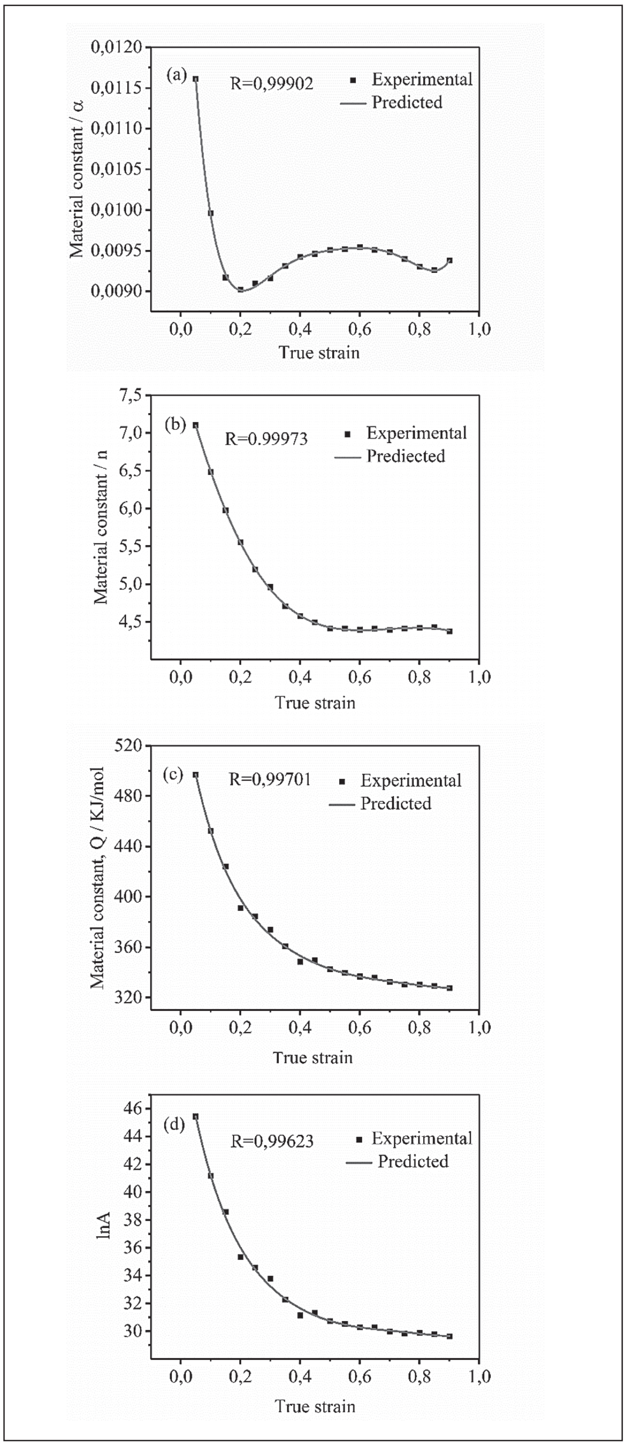

Figure 4 Relationships between material constants (a) α, (b) *n*, (c) *Q*, (d) *lnA* and true strain.

According to the experimental data, Q, n and In A. 0,05 - 0,90 were calculated within the strain range. The data in Table 2 confirms this.

$$P = k_0 + k_1\varepsilon + k_2\varepsilon^2 + k_3\varepsilon^3 + k_4\varepsilon^4 + \varepsilon^5 + k_6\varepsilon^6 + \cdots \tag{11}$$

The polynomial order must be an integer between 1 and 9 [6]. Through research, the number of polynomials was determined to be 6. The coefficients of the fitted polynomial are shown in Table 3. Figure 4 shows a fitted graph of the data. It can be seen that the fitted curve has a good correlation.

According to Equation (9), the constitutive equation of 42CrMo gear steel can be known as follows:

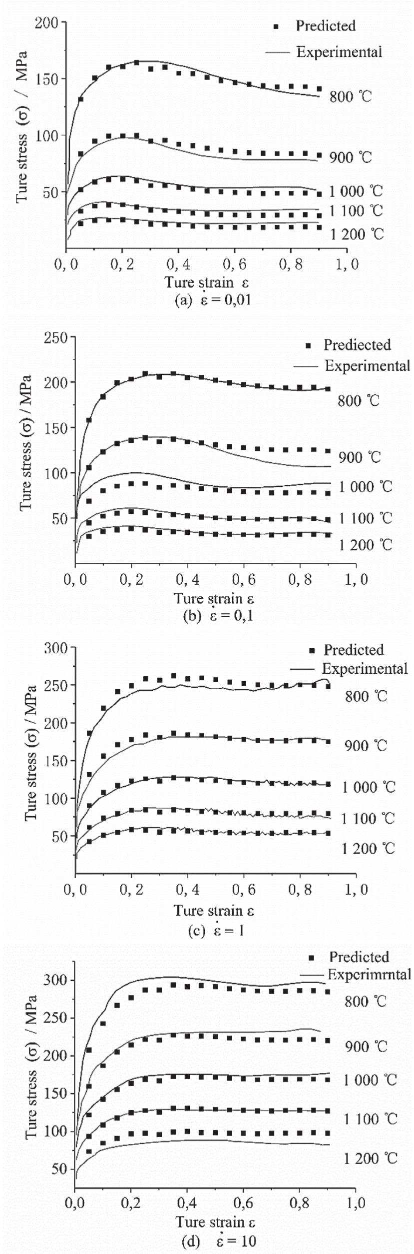

Figure 5 Predicted flow curves and comparison with experimentally obtained

$$\sigma = \frac{1}{\alpha}\ln\left\{(\frac{Z}{A})^{\frac{1}{n}} + [\left(\frac{Z}{A}\right)^{\frac{2}{n}} + 1]^{\frac{1}{2}}\right\} \quad (12)$$

Among them, the parameters: α, n, Q and A are as above.

As can be seen from Figure 5, the predicted values are highly consistent with the experimental values.

$$R = \frac{\sum_{i=1}^{N}(E_i - E)(P_i - P)}{\sqrt{\sum_{i=1}^{N}(E_i - \bar{E})^2(P_i - \bar{P})^2}} \quad (13)$$

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

In these equations, E is the experimental flow stress, P is the predicted flow stress, $\bar{E}$ and $\bar{P}$ is the average of E and P.

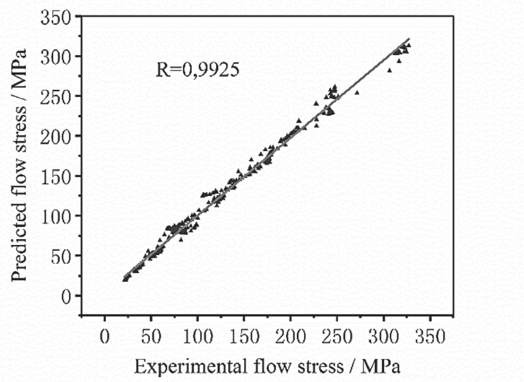

Figure 6 Correlation between the predicted and experimental flow stresses for the strain range of 0,05 – 0,9 (at intervals of 0,05) over the entire strain rate (0,01 – 10 s^{-1}) and deformation temperature range (800 – 1 200 °C).

Figure 6 shows good data correlation. R is 0,9 925 and AARE / % is 4,928 %. This indicates that the Arrhenius-type constitutive equation has a highly prediction accuracy for the flow stress of 42CrMo gear steel.

CONCLUSIONS

(1) Deformation temperature and strain rate have significant influence on the stress and strain curve of 42CrMo geal geel, and the values of flow stress will increase as the strain rate increases, and decreases as the deformation temperature increases.

(2) The strain-compensationed Athenius constitutive model of the 42CrMo gear steel constructed can predict highly its flow stress. R = 0,9 925, AARE = 4,928 %.

Acknowledgments

This project is supported by the Hebei Provincial Department of Education Youth Talents Project (BJ2 019 010) and funded by the China Postdoctoral Science Found (201 8M6 411 86)

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