THE ARRHENIUS CONSTITUTIVE MODEL OF STEEL 42CrMo FOR GEAR

Thermal compression test temperature ranged from 800 to 1200 °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-compensated 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 gear-box 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 1500D thermomechanical simulator was used for thermal compression at temperatures of 800 °C, 900 °C, 1000 °C and 1200 °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>
<thead>
<tr>
<th>Chemical composition of 42CrMo /wt. %</th>
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<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>0.38 - 0.45</td>
</tr>
<tr>
<td>Ni</td>
</tr>
<tr>
<td>≤ 0.30</td>
</tr>
</tbody>
</table>

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 $\sigma$ can be expressed by a hyperbolic sine function.

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

There are different equations at different pressure levels.

1) At low stress levels ($\sigma < 0.8$):

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

2) At high stress levels ($\sigma > 1.2$):

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

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

$$\dot{\varepsilon} = A_3 \sinh(\sigma) \exp \left( -\frac{Q}{RT} \right)$$ (4)
In these equations, $\dot{\varepsilon}$ is the strain rate; $A, A_1, A_2$ are material constants; $\alpha$ is the stress factor ($\alpha = \beta/n'$), $\sigma$ is the flow stress; $n'$ is the stress index; $Q$ is the thermal deformation activation energy; $R$ is the molar gas constant, $R = 8,314 \text{ J/(mol} \cdot \text{K})$; $T$ 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, $\beta = 0,065$. According to ($\alpha = \beta/n'$), $\alpha = 0,009$ is obtained. Take the logarithm of Equation (4):

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

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

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

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

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

From Figure 2, these data can be obtained: $n = 5,245$, $Q = 366 \times 10^4 \text{ J/mol}$. The relationship between stress, strain rate and deformation temperature is described using the Zener-Hollomon parameter [4] as follows:

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

Simultaneous Equation (4) and Equation (8):

$$\dot{\varepsilon} = 4,171 \times 10^4 \left[ 0,009 \sinh (\sigma_p) \right]^{2,245}$$

Figure 1 Flow stress-strain curves of 42CrMo

Figure 2 Relationships between (a) and ; (b) and ; (c) and ; (d) and $1/T$;
According to the relationship of \( \ln Z - \ln[\sinh(\alpha \sigma)] \), linear regression is performed, and Figure 3 can be obtained. According to the fitting curve, the intercept \( A = 4.171 \times 10^{14} \) 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):

\[
\exp \left( -\frac{366 \times 10^8}{8.3147} \right)
\]

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. 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:

\[
P = k_0 + k_1 \varepsilon + k_2 \varepsilon^2 + k_3 \varepsilon^3 + k_4 \varepsilon^4 + k_5 \varepsilon^5 + \cdots
\]

According to the experimental data, \( Q \), \( n \) and \( \ln A \) were calculated within the strain range. The data in Table 2 confirms this.
Among them, the parameters: $\alpha$, $n$, $Q$ and $A$ are as above.

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

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

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

Figure 6 shows good data correlation. $R = 0.9925$ 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 gear steel, and the values of flow stress will increase as the strain rate increases, and decreases as the deformation temperature increases.

(2) The strain-compensationed Arrhenius constitutive model of the 42CrMo gear steel constructed can predict highly its flow stress. $R = 0.9925$, AARE = 4.928 %.

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REFERENCES


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