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CONSTITUTIVE MODEL OF AISI 1035 AT HIGH TEMPERATURE

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Use Gleeble-1500D thermal simulation test machine to conduct thermal tensile test on AISI 1035 in the deformation temperature range of 1 173,15~1 373,15 K and strain rate range of 0,2 ~ 20 s^{-1}. Using the obtained true stress-strain curves, an intrinsic model of the material was constructed using a model considering strain compensation. The results showed that the correlation coefficient of the Arrhenius model of AISI 1035 considering strain compensation was 0,984 with an average absolute error of 3,550 %, which can accurately predict the flow profitability. The experimental data matched well with the prediction curves obtained from the model calculation, which verified the feasibility of the model.

Keyword: AISI 1035; compression test; stress-strain curves; intrinsic structure model; flow behavior

INTRODUCTION

The high-temperature flow behavior of materials is the most important basis for the construction and analysis of intrinsic constitutive relationships, providing the basis for the study of various material processing techniques [1]. Generally, intrinsic constitutive models quantitatively reveal the essential relationships between flow stresses and thermo-mechanical state variables, such as strain, strain rate, and temperature. Furthermore, based on this, the complex deformation behavior of materials during thermal processing can be accurately analyzed, thus facilitating the design and optimization of processing processes [2]. Therefore, it is of great practical importance to study and develop the intrinsic structure relationship of the material. Although AISI 1035 is widely used, there is a great lack of comprehensive intrinsic structure analysis of AISI 1035 flow behavior and no effective and accurate AISI 1035 intrinsic structure model, which limits its further application. Therefore, there is an urgent need for an AISI 1035 intrinsic constitutive model that can accurately predict flow stresses in the full strain range in mechanical manufacturing technology research and practical industrial production [3]. By introducing the Z parameter in the intrinsic constitutive model, the prediction of the Arrhenius model can maintain high accuracy under various complex deformation conditions, and therefore the Arrhenius model has been widely used, especially at high temperatures [4-6].

In this paper, hot compression tests were conducted over a wide range of strain rates and temperatures to study the flow behavior of 35-gauge steel. Based on this, an Arrhenius model considering strain compensation is developed, and the dependence of material constants on strain is discussed in depth. Finally, the accuracy and generality of the established intrinsic structure model are verified and analyzed.

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EXPERIMENTAL MATERIALS AND PROCESSES

AISI 1035 is one of the representative medium carbon steel. Due to its good balance of strength, toughness and wear resistance, it is widely used for many general purpose parts including automotive crankshaft, rams, spindles, etc. The chemical compositions of AISI 1035 steel are 0,32 % C,0,79 % Mn,0,89 % Si, 0,01 % S, 0,021 % P.

Isothermal compression tests under different conditions were performed using a Gleble-1500D simulator, and parameters such as displacement and stress were measured and recorded. The experimental temperature was set as 1 173,15K,1 273,15K, 1 373,15K, the strain rate was set as 0,2 s^{-1}, 2 s^{-1} and 20 s^{-1}.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

Figure 1 shows the effect of strain rate on the behavior of the flow stress. From the figure, it can be seen that when the temperature is constant, the flow stress increases as the strain rate increases. The flow stress is very sensitive to the strain rate. At low strain rates, the flow stress increases with increasing strain rate. At higher strain rates, it still increases, but at a slower rate due to the softening effect of increasing material temperature.

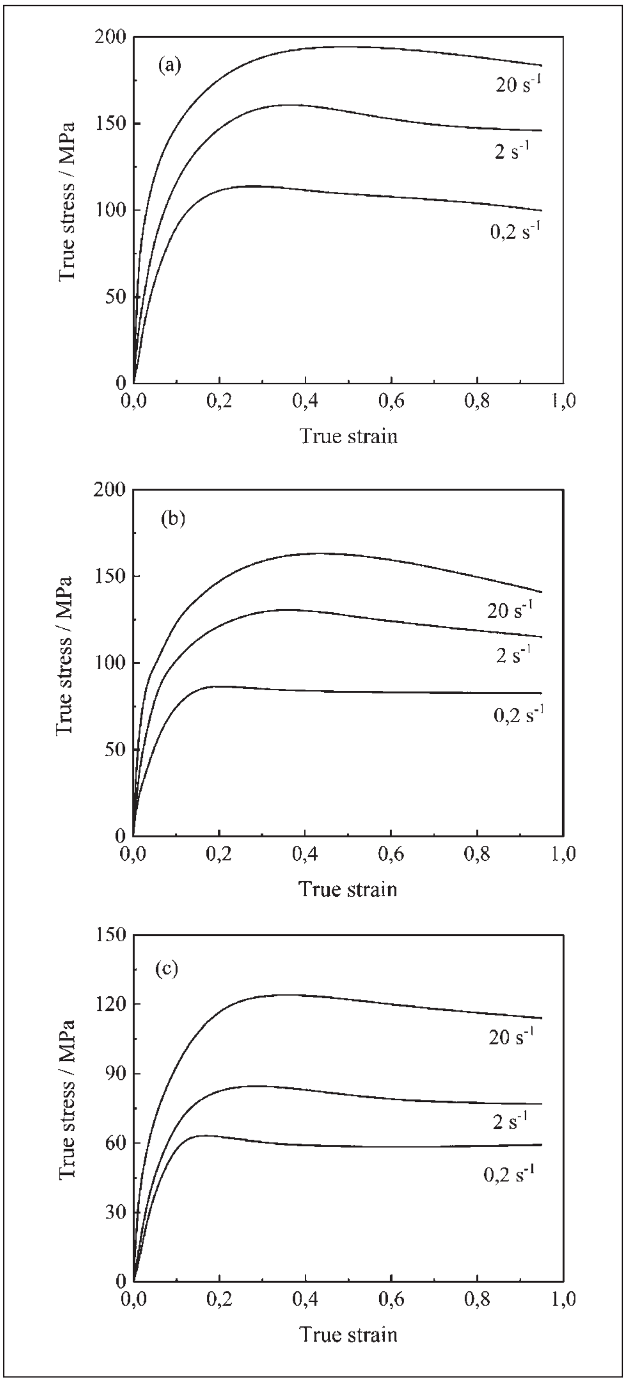


Figure 1 Stress-strain curves of AISI 1035 at different temperatures: (a) T = 900 °C; (b) T = 1 000 °C; (c) T = 1 100 °C

It has been verified by a large number of scholars that the rheological stresses in the hot forming process of metallic materials are related to a variety of factors. The reasons can be divided into two categories: one of them is the deformation parameter and the other is the elemental composition of the metallic material [7-9]. In the thermal deformation process, the composition of the metal tissue is constant, then the heat deformation parameters, can be expressed as a double sine function:

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

Depending on the stress level corresponds to different equations:

1) At low stress levels (ασ<0,8), equation (1) simplifies to:

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

2) At high stress levels (ασ>1,2), equation (1) simplifies to:

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

3) Equation (1) at full stress level is simplified as:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n\exp\left(-\frac{Q}{RT}\right) \tag{4}$$

where: $\dot{\varepsilon}$ - strain rate / s^{-1}; A, A_1, A_2-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.

Thermal deformation activation energy Q and material dependent constant A are independent of the temperature. At the whole stress level, the hyperbolic functional relationship equation (4) is most commonly used to describe.

Taking the natural logarithm of both sides of equation (3):

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

It can be seen that when the temperature is certain, $\ln\left[\sinh(\alpha\sigma)\right]$ - shows a certain linear relationship:

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

Similarly, when the strain rate is a constant value, ln[sinh(ασ)] and 1/T show a certain linear relationship:

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

The Zener-Hollomon parameter is used to describe the relationship between stress, strain rate and deformation temperature as:

$$Z = \dot{\varepsilon}\cdot\exp\left(\frac{Q}{RT}\right) \tag{8}$$

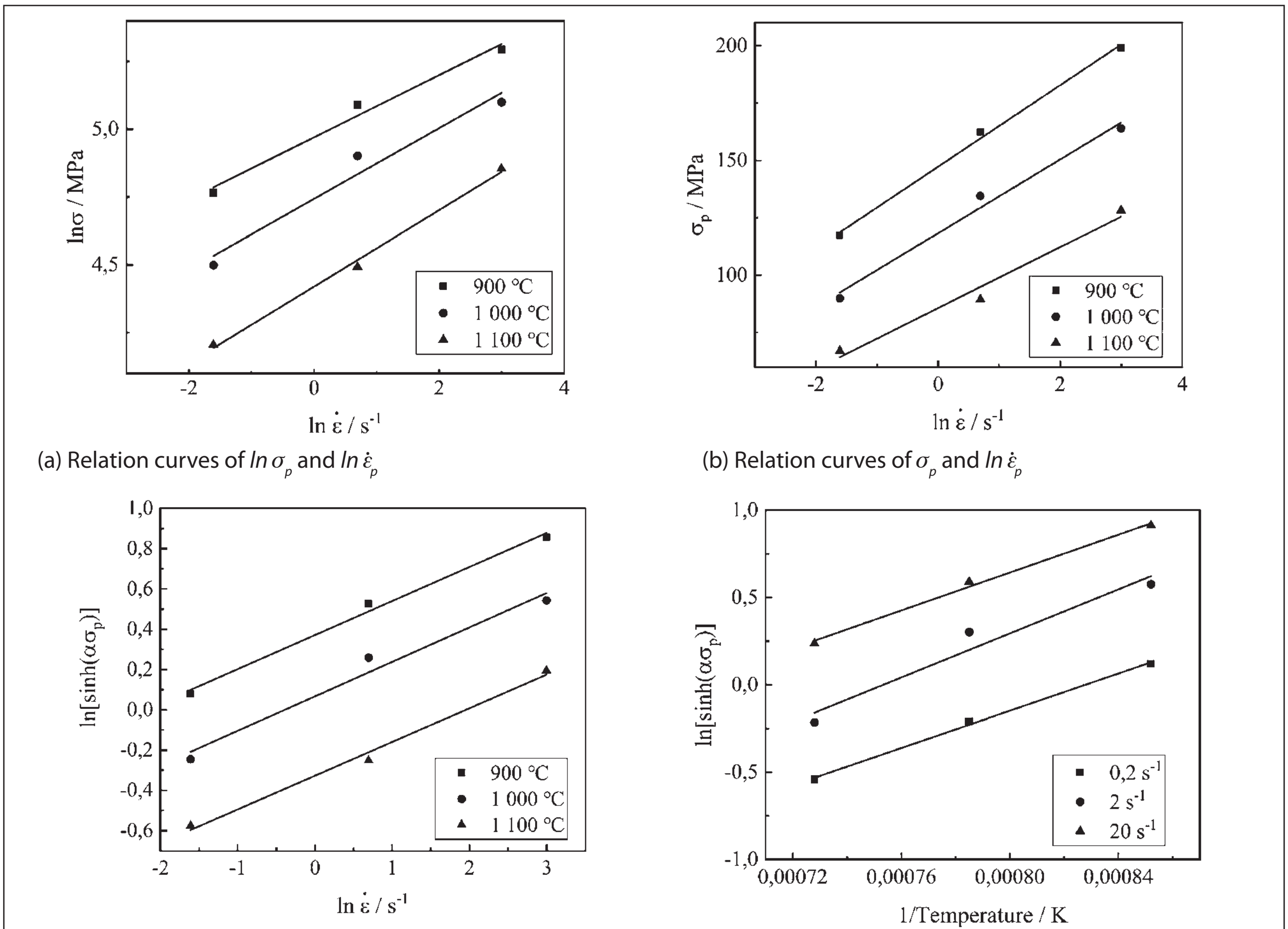
$$\ln Z = \ln A + n\ln[\sinh(\alpha\sigma)] \tag{9}$$

A scatter plot between $\ln Z$ and $\ln\left[\sinh(\alpha\sigma)\right]$ is plotted and a linear regression is performed on the data points, as shown in Figure 3.

The correlation of their fitted straight lines is as high as 98,6 %. This can show that lnZ and ln[sinh(ασ)] have a good linear relationship. The intercept of the fitted straight line is taken as 26,06793. This value is the value of lnA, which gives A = 2,9488×10^{11}.

Substituting the parameters back into equation (4), we can get AISI 1035 high temperature heat deformation peak stress instanton equation:

$$\dot{\varepsilon} = 2{,}9488\times10^{11}[0{,}008\sinh(\sigma_p)]^{5{,}914718594}$$
$$\exp\left(-\frac{279514{,}4478}{8{,}314T}\right) \tag{10}$$



(a) Relation curves of $ln\,\sigma_p$ and $ln\,\dot{\varepsilon}_p$

(b) Relation curves of σ_p and $ln\,\dot{\varepsilon}_p$

(c) Relation curves of $ln[sinh(\alpha\sigma)]$ and $ln\,\dot{\varepsilon}$

(d) Relation curves of $ln[sinh(\alpha\sigma)]$ and 1/T

Figure 2 Fitting of each parameter

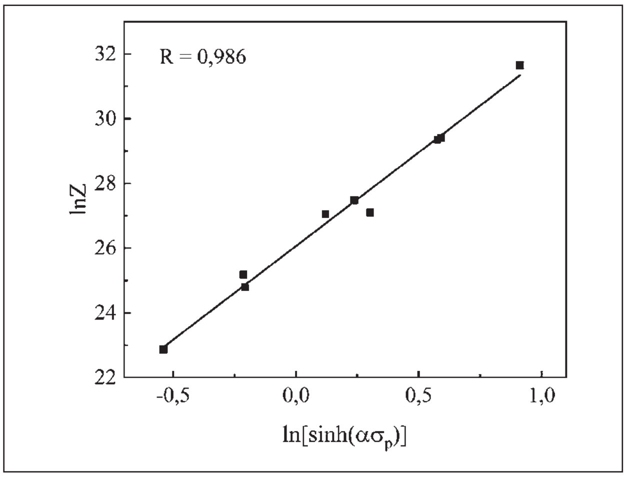


Figure 3 Relation curves of *lnZ* and $ln[sinh(\alpha\sigma)]$

SIMULATION PREDICTION AND VERIFICATION OF CONSTITUTIVE MODEL

To improve the accuracy of equation prediction, strain factors were introduced into the Arrhenius equation to establish a more accurate strain-coupled intrinsic structure model. Based on the AISI 1035 data, Q, n, α and lnA were calculated for different strains of AISI 1035.

The rheological stresses under the corresponding deformation parameters can be found by bringing the requested parameters into equation (12) at different strains. With this model, the rheological stresses predicted by the formula are calculated and compared with the experimental data as shown in Figure 4.

In order to more accurately quantify and compare the prediction accuracy of the two constitutive equations established, it is necessary to perform statistical error analysis on the prediction data and experimental data. Introduce two statistical parameters: correlation coefficient (R) and average absolute error (δ_{AARE}) to further evaluate the predictive ability of the model:

$$R=\frac{\sum_{i=1}^{N}\left(E_i-\overline{E}\right)\left(P_i-\overline{P}\right)}{\sqrt{\sum_{i=1}^{N}\left(E_i-\overline{E}\right)^2\times\left(P_i-\overline{P}\right)^2}} \tag{11}$$

$$\delta_{\mathrm{AARE}}=\frac{1}{N}\sum_{i=1}^{N}\left|\frac{E_i-P_i}{E_i}\right|\times 100\% \tag{12}$$

where: E_i is the experimental value; P_i is the predicted value; $\overline{E}$ and $\overline{P}$ are the average of the experimental value and the predicted value; N is the number of samples.

The correlation coefficient (R) is usually used to reflect the ability of the linear relationship between the experimental data and the predicted data. A good data correlation is demonstrated in Figure 5 with a correlation coefficient (R) value of 0,984 and an AARE / %

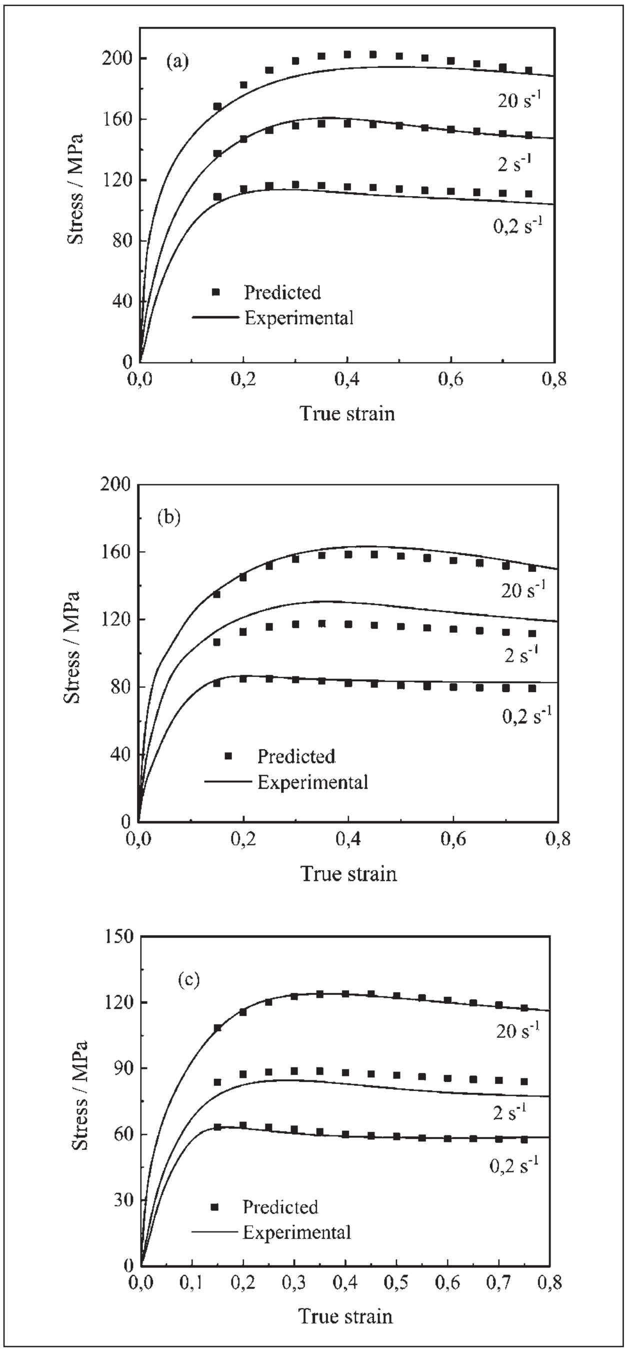


Figure 4 Comparison of predicted value and experimental value. (a) T = 900 °C; (b) T = 1 000 °C; (c) T = 1 100 °C.

value of 3,550 %. This indicates that the Arrhenus instantonal equation has a high prediction accuracy for the rheological stress of AISI 1035.

CONCLUSION

AISI 1035 is sensitive to changes in temperature and strain rate, the higher the temperature, the lower the strain rate, the smaller the value of the corresponding flow stress.

The intrinsic structure model of AISI 1035 in the selected full strain range was developed considering strain compensation and introducing Zener-Holomon parameters. Its accuracy, generality and applicability are analyzed and verified. The results show that the intrinsic

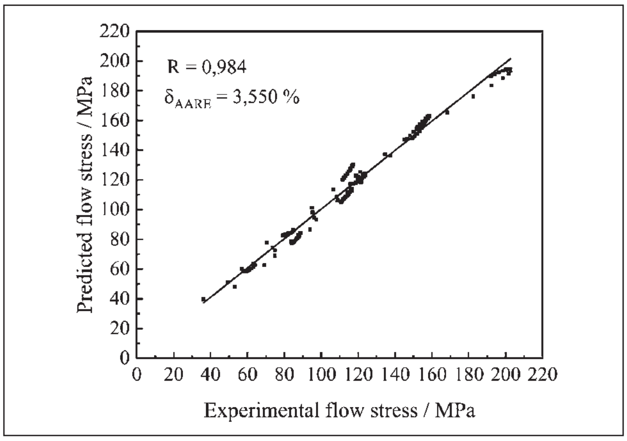


Figure 5 Correlation test between predicted value and experimental value

structure model established in this paper has a high accuracy.

Acknowledgments

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Note: The responsible translator for English language is Z. S. Peng -North China University of Science and Technology, China