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An adaptive constitutive model in the isothermal compression of Ti600 alloy

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ABSTRACT

The Ti600 alloy was isothermally compressed at the deformation temperatures ranging from 800 °C to 1000 °C with an interval of 40 °C, the strain rates of 0.001 s^{-1}, 0.01 s^{-1}, 0.1 s^{-1}, 1.0 s^{-1}, 10.0 s^{-1} and a height reduction of 50% on a Gleeble-1500D thermo-mechanical simulator. Based on the experimental flow stress, a fuzzy neural network model (FNN model) was developed to acquire the constitutive model in the isothermal compression of Ti600 alloy. In the present constitutive model, the three inputs of FNN model are, respectively, the deformation temperature, the strain rate and the strain, and the output of FNN model is the flow stress. The predicted flow stress is in a good agreement with the experimental flow stress, meanwhile the predicted accuracy of flow stress in the isothermal compression of Ti600 alloy using the FNN model is higher than that using the regression model.

1. Introduction

The understanding of deformation behavior in high temperature deformation has a great importance for optimizing the deformation processes because of its effective role on the flow pattern as well as the kinetics of metallurgical transformation. In the past years, there are consistent efforts to develop constitutive model, which would give a complete mathematical description of the flow stress of metals and alloys. Vo et al. had successfully validated the flow stress model using a self-consistent method according to the experimental and literature data of IMI834 alloy [1]. Wei et al. analyzed the stress–strain relationship for strain hardening and softening by combining the Estrin and Mecking (EM) model and an Avrami-type equation with experimental data in severe plastic deformation of aluminum and copper [2]. Slooff et al. had evaluated the effect of the experimental correction on the constitutive behavior of $Mg–Al_4–Zn_1$ wrought magnesium alloy [3]. Zhou used the grain size as internal variable to characterize the resulting flow softening and to model the constitutive relationship in high temperature forging of IMI834 alloy [4].

The response of deformation behaviors to the process parameters at the deformation temperatures and strain rates is highly nonlinear, and the effect of process parameters on the flow stress is also highly nonlinear. The artificial neural network method unlike the regression method does not need a mathematical formulation, and its key characteristic is the capability of self-organization or 'learning'. The artificial neural network approach is especially suitable for treating the nonlinear phenomena and complex system, and has been successfully applied to establish the constitutive model of metals and alloys. Li et al. had acquired the relationships between the mechanical properties and the deformation technological parameters of Ti–6Al–6V–2Sn alloy using the isothermal compression and the standard tension data of forged Ti–6Al–6V–2Sn alloy in terms of the artificial neural networks (ANNs) [5]. Malinov and Sha illustrated the examples for optimization of the alloy compositions, processing parameters and working conditions of titanium alloys and γ-titanium aluminides based on the correlation between processing parameters and properties [6]. Reddy et al. had developed a back-propagation neural network model to predict the flow stress in the hot deformation of Ti–6Al–4V alloy at any given processing conditions [7]. The artificial neural network can be trained, but it is extremely difficult to use a prior knowledge about the system under consideration and it is impossible to explain the neural system in a particular situation. In order to compensate for the drawbacks of ANN approach, the fuzzy systems are combined with the artificial neural networks. Li et al. had established an adaptive constitutive relationship in isothermal compression of Ti–6.29Al–2.71Mo–1.42Cr alloy using fuzzy neural network approach [8]. Luo et al. modeled the flow stress, grain size and volume fraction in the isothermal compression of Ti–6.62Al–5.14Sn–1.82Zr alloy using fuzzy neural network with a back-propagation learning algorithm [9]. Chen et al. had established an adaptive fuzzy neural network model to characterize the constitutive relation in the superplastic deformation of 15 vol% SiCp/LY12 aluminum composite [10]. Kumar et al. established a hybrid neural network model using recurrent self-organizing neural network to predict the flow stress for carbon steels [11].

Many investigations have been conducted to characterize the deformation behavior of high temperature titanium alloys. Li et al. characterized the high temperature deformation behavior of

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Ti–5.6Al–4.8Sn–2.0Zr alloy based on the stress–strain behavior, kinetics and processing map of isothermal compression [12]. Weiss and Semiatin had achieved the microstructure control and deformation uniformity in the α and near-α titanium alloys processing through the selection of optimum processing conditions with the aid of processing maps [13]. Wanjara et al. obtained the constitutive equations using an Arrhenius-type hyperbolic–sine relationship according to the experimental flow stress in the isothermal compression of IMI834 alloy [14]. The Ti600 alloy is a novel near α high temperature titanium alloy. Niu et al. had obtained the flow stress, apparent activation energy for deformation, constitutive equation and processing map in the isothermal compression of Ti600 alloy [15]. The deformation behavior in high temperature compression of Ti600 alloy need to be further investigated to study the workability and optimize the process parameters, especially for the high prediction accuracy and wide applicable range.

In this paper, a FNN model of the flow stress based on the fuzzy set and artificial neural network have been developed to establish the constitutive model between the flow stress and the process parameters in the isothermal compression of Ti600 alloy. Meanwhile, a comparison of the predicted flow stress using the FNN model with that using the regression model has been carried out.

2. Experimental procedures

The as-received Ti600 alloy (Ti–6Al–2.8Sn–4Zr–0.5Mo–0.4Si–0.1Y, wt%) is 12.0 mm in diameter. The as-received Ti600 alloy was treated in the following procedures: (1) heated to 850 °C and hold 1 h, (2) cooled in air to room temperature. Cylindrical specimens with 12.0 mm in height and 8.0 mm in diameter were machined from the treated Ti600 alloy. Isothermal compression at a constant strain rate was conducted on a Gleeble-1500D thermo-mechanical simulator at the deformation temperatures ranging from 800 °C to 1000 °C with an intervals of 40 °C, a height reduction of 50% and the strain rates of 0.001 s^{-1}, 0.01 s^{-1}, 0.1 s^{-1}, 1.0 s^{-1} and 10.0 s^{-1}. The Ti600 alloy specimens were heated at a heating rate of 10 °C s^{-1} and hold 3 min prior to compression. The specimens were isothermally compressed to a height reduction of 50% and cooled in air to room temperature. In isothermal compression, the flow stress was recorded as a function of strain at each deformation temperature and strain rate.

The selected stress–strain curves obtained at the deformation temperatures of 840 °C, 920 °C, 1000 °C and the strain rates ranging from 0.001 s^{-1} to 10.0 s^{-1} are presented in Fig. 1(a–c), respectively. The stress–strain curves showed a peak flow stress at low strain, a regime of noticeable flow softening, and near steady state flow at large strain. The effect of deformation temperature on the peak flow stress in isothermal compression of Ti600 alloy is shown in Fig. 2. The peak flow stress increased with the decreasing of deformation temperature, and the increasing rate of peak flow stress decreased with the decreasing of strain rates ranging from 10.0 s^{-1} to 0.001 s^{-1}. As seen from Figs. 1 and 2, it can be seen that the flow stress in the isothermal compression of Ti600 alloy is sensitive to strain rate, deformation temperature and strain.

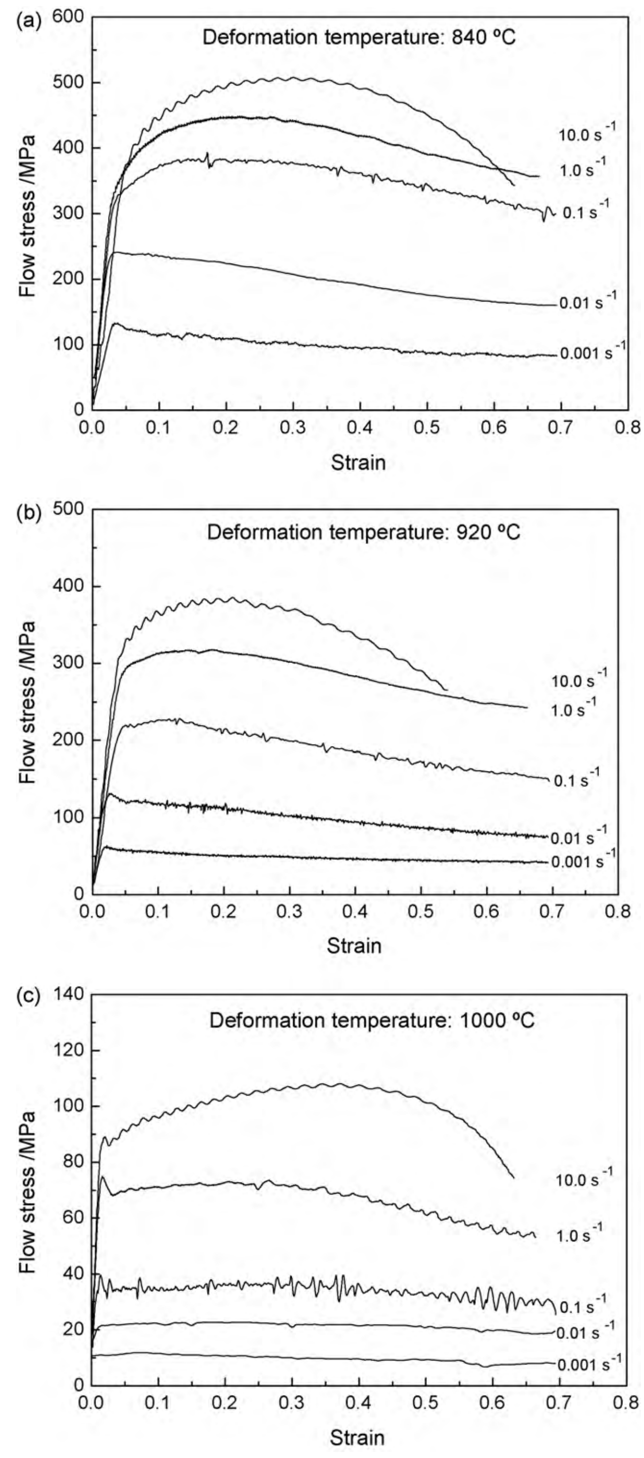

Fig. 1. Typical stress–strain curves in the isothermal compression of Ti600 alloy at different deformation temperatures of: 840 °C (a), 920 °C (b) and 1000 °C (c).

3. The constitutive model

The FNN is an intelligent information-treatment system with the characteristic of adaptive learning capable of treating the complex and nonlinear relationships. The FNN structure schematic for predicting the flow stress in the isothermal compression of Ti600 alloy is shown in Fig. 3. In the model structure shown in Fig. 3, the three inputs including deformation temperature (T, °C), strain rate ($\log \dot{\varepsilon}$, s^{-1}) and strain (ε), are designated as x_1, x_2, x_3, while the output denoted as Y is the flow stress (σ, MPa) in the isothermal compression of Ti600 alloy.

The activation function in the output layer of this model is a linear function, while the activation function in the hidden layer is selected to be a sigmoid function in the following form:

$$\mu_j^i = \exp\left[\frac{-(x_j - a_j^i)^2}{b_j^i}\right] \quad (1)$$

where a_j^i and b_j^i are the constants.