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Application of neural networks to predict the elevated temperature flow behavior of a low alloy steel

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Abstract

In order to study the workability and establish the optimum hot forming processing parameters for 42CrMo steel, the compressive deformation behavior of 42CrMo steel was investigated at the temperatures from 850 °C to 1150 °C and strain rates from 0.01 s^{-1} to 50 s^{-1} on Gleeble-1500 thermo-simulation machine. Based on these experimental results, an artificial neural network (ANN) model is developed to predict the constitutive flow behaviors of 42CrMo steel during hot deformation. The inputs of the neural network are deformation temperature, log strain rate and strain whereas flow stress is the output. A three layer feed forward network with 12 neurons in a single hidden layer and back propagation (BP) learning algorithm has been employed. The effect of deformation temperature, strain rate and strain on the flow behavior of 42CrMo steel has been investigated by comparing the experimental and predicted results using the developed ANN model. A very good correlation between experimental and predicted result has been obtained, and the predicted results are consistent with what is expected from fundamental theory of hot compression deformation, which indicates that the excellent capability of the developed ANN model to predict the flow stress level, the strain hardening and flow softening stages is well evidenced.

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Keywords: 42CrMo steel; Artificial neural networks; Back propagation (BP) learning algorithm; Hot compression deformation; Flow stress

1. Introduction

During hot forming process of material, several interconnect metallurgical phenomena such as working hardening, dynamic recovery, dynamic recrystallization etc occur. The hardening and softening mechanisms are both significantly affected by the temperature and strain rate. Therefore, the constitutive flow behaviors of materials is quite complex in nature [1–4]. The understanding of metals and alloys behavior at hot deformation condition has a great importance for designers of metal forming processes (hot rolling, forging and extrusion) because of its effective role on metal flow pattern as well as the kinetics of metallurgical transformation. In the past, there are consistent efforts to develop constitutive equations, which would give a complete mathematical description of the flow stress of materials [4–10]. The conventional methods are to carry out the regression analysis with the experimental results on the basis of the models to obtain the constants in the models. However, the response of the deformation behaviors of the materials under elevated temperatures and strain rates is highly nonlinear, and many factors affecting the flow stress are also nonlinear, which make the accuracy of the flow stress predicted by the regression methods low and the applicable range limited. However, the field of neural networks can be thought of as being related to artificial intelligence, machine learning, parallel processing, statistics, and other fields. The attraction of artificial neural networks (ANN) is that they are best suited to solving the

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problems that are the most difficult to solve by traditional computational methods. Neural networks can provide a fundamentally different approach to materials modeling and material processing control techniques than statistical or numerical methods. One of the main advantages of this approach is that it is not necessary to postulate a mathematical model at first or identify its parameters using a neural network. Some efforts have been made to the applications of neural networks in industry or academic study [11–16].

42CrMo (American grade: AISI 4140) is one of the representative medium carbon and low alloy steel. Due to its good balance of strength, toughness and wear resistance, 42CrMo high-strength steel is widely used for many general purpose parts including automotive crankshaft, rams, spindles, etc. In the past, many investigations have been carried out on the behavior of 42CrMo steel [4,17–21]. Lin et al. [4] derived a revised constitutive equation incorporating the effects of deformation temperature, strain rate and deformation degree by compensation of strain and strain rate. Lin et al. [17] established the flow stress constitutive equations of the work hardening-dynamical recovery period and dynamical recrystallization period. Kim and Yoo [19] established the quantitative relationships between the flow stress and the volume fraction of dynamic recrystallisation (DRX) as a function of processing variables such as strain rate, temperature, and strain for AISI type 4140 medium carbon steel, by means of torsion tests. Lin et al. [20] studied the effects of processing parameters, including the strain rate, forming temperature and deformation degree, on the microstructures of 42CrMo steel by metallurgical analysis. Despite large amount of efforts invested into the behavior of 42CrMo steel, the hot compressive deformation behavior of 42CrMo steel need to be further investigated to study the workability and optimize the hot forming process parameters for 42CrMo steel, especially for the high prediction accuracy and wide applicable range.

The object of this study is to develop an efficient artificial neural network (ANN) model to predict the constitutive flow behaviors of 42CrMo steel during hot deformation, and investigate the general nature of the influence of strain, strain rate and temperature on the compressive deformation characteristics of 42CrMo steel. The capability of the developed ANN model to predict the flow stress level, the strain hardening and flow softening stages is also investigated.

2. Experiments

A commercial 42CrMo high-strength steel of compositions (wt.%) 0.450C–0.280Si–0.960Cr–0.630Mn–0.190 Mo–0.016P–0.012S–0.014Cu–(bal.)Fe was used in this investigation. Cylindrical specimens were machined with a diameter of 10 mm and a height of 15 mm, as shown in Fig. 1. In order to minimize the frictions between the specimens and die during hot deformation, the flat ends of the specimen were recessed to a depth of 0.2 mm deep to entrap the lubricant of graphite mixed with machine oil. The hot compression tests were performed on Gleeble-1500 thermo-simulation machine in the four different temperatures (850, 950, 1050 and 1150 °C) and four different strain rates (0.01, 0.1, 1, 10 and 50 s^{-1}). Each specimen was heated to the deformation temperature at a rate of 10 °C/s by thermo-coupled feedback-controlled AC current, and held for 5 min at isothermal conditions before compression tests, in order to obtain the heat balance. The reduction in height is 60% at the end of the compression tests. The load-displacement data were recorded automatically by the computer control system of the thermal simulator. Then, true stress–strain curves of 42CrMo steel can be easily transformed from the load-displacement data recorded by the thermal simulator during hot compression test. Fig. 2 shows the typical true stress–strain curves obtained from hot compression tests of 42CrMo steel.

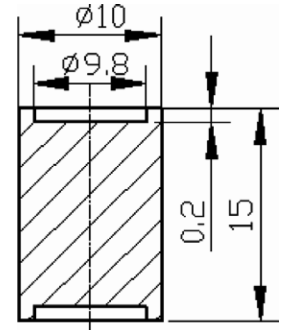

Fig. 1. Dimension of specimen (unit: mm).

3. Development of ANN for flow stress prediction of 42CrMo steel

3.1. Theory of artificial neural network (ANN)

Artificial neural networks (ANN) are a large class of parallel processing architectures, which can mimic complex and nonlinear relationships through the application of many nonlinear processing units called neurons. The relationship can be 'learned' by a neural network through adequate training from the experimental data. It can not only make decisions based on incomplete and disorderly information, but can also generalize rules from those cases on which it was trained and apply these rules to new cases. Usually, the structure of an ANN is hierarchical with neurons grouped in different layers designed as an input layer, hidden layers and on output layer, as shown in Fig. 3. Signals are supplied to the neurons of the input layer; each neuron of this layer then generates an output signal, which is transferred to the neurons of the hidden layer. The output signals are generated by the last layer (output layer). Of course, there is no theoretical limit on the number of hidden layers but typically there is just one or two. A maximum of four layers (three hidden layers plus an output layer) are enough to solve problems of any complexity.