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Modelling of the hot deformation behaviour of a titanium alloy using constitutive equations and artificial neural network

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ABSTRACT

Hot deformation characteristics of a Ti600 titanium alloy were investigated by a Gleeble 1500D thermo-mechanical test simulator over the temperature range from 760 to 920 °C and strain rate range from 0.01 to 10 s^{-1}. The flow behaviour and microstructural evolution were studied. Dynamic recrystallisation (DRX) grains exhibit different shapes at different deformation temperatures, and more severe distortion around the DRX grains exists in the matrix deformed at low temperature compared with that at relatively high temperature. Phenomenological and empirical constitutive equations were established based on the hyperbolic sine Arrhenius-type model and the multiple-linear regression, respectively. An artificial neural network (ANN) model was developed to predict the flow stress. A comparative study was made on the capability of the developed models to represent the hot deformation behaviour of this alloy. The results indicate that the flow stress of Ti600 alloy is sensitively dependent on the strain rate and deformation temperature. The multiple-linear model shows a higher accuracy in tracking the flow behaviour of Ti600 alloy than the Arrhenius-type model. The ANN model is much more efficient and has higher accuracy in predicting the hot deformation flow behaviour of Ti600 alloy than both the Arrhenius-type and multiple-linear models.

1. Introduction

Hot deformation of metals is extensively performed in the manufacture of final products with desired geometry and required properties. The hot deformation behaviours of metals are always accompanied with various interconnecting metallurgical phenomena such as flow instability [1], work hardening [2], dynamic recrystallisation (DRX) [3] and dynamic recovery (DRV) [4]. Work hardening increases the flow stress of metals and reduces the ductility, while the phenomena like DRX or DRV cause dynamic softening in metals and thereby restore the ductility. Flow instability is generally associated with a form of unstable mechanical flow, and may produce shear zone/internal cracks, which will become the sites for eventual failure of the metals during hot deformation as well as in service. An excellent design of an industrial hot working process is ensured by an in-depth understanding of the dependence of flow stress behaviour on the deformation parameters, i.e. strain, strain rate and temperature, due to its effective role on the metallurgical characterisations. The determination of the relationship between the flow stress and deformation parameters is of critical importance to the optimisation of hot working conditions with a purpose of acquiring the required final microstructure and mechanical properties. The flow stress, which changes with strain, strain rate and temperature, of metals during hot deformation has received great attentions, and numerous efforts have been made to characterise flow behaviours by physical and mathematical simulative techniques [5–7]. The quantitative relationship between the flow stress and deformation parameters plays a crucial role in the successful modelling of deformation process by using a numerical simulation method. Over the past decades, a lot of investigations have been conducted on the constitutive modelling of plastic flow behaviour of metals in hot deformation [8,9].

At present, three types of constitutive models including analytical [10], phenomenological [11,12] and empirical [13,14] ones are generally employed to model the flow behaviour of metals at elevated temperatures. With regard to titanium alloys, Fan and Yang [15] proposed an internal-state-variable based self-consistent analytical constitutive model for the hot working of Ti–6Al–4V and

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IMI834 titanium alloys in both single-beta region and two-phase region by considering the underlying deformation mechanism and microstructural evolution, and the model predictions were found to be in good agreement with experimental results. For predicting the hot deformation behaviour and microstructure of TA15 titanium alloy, Fan et al. [16] developed an analytical constitutive model by coupling dislocation density evolution, static and dynamic grain coarsening, strain induced grain refinement, and loss of Hall–Petch strengthening. This constitutive model has a relatively high prediction precision, and can be used to represent effectively the flow stress, phase fraction and grain size of each phase of titanium alloy during hot deformation. Among the phenomenological models, Arrhenius-type constitutive equations and their modified forms were employed extensively by many researchers in the modelling of hot deformation behaviour of pure titanium [17], and Ti600 [18], Ti–6Al–4V [19], Ti60 [20], IMI834 [21] and Ti-–6Al–7Nb [22] titanium alloys. These models are more reliable in the prediction of hot deformation behaviour of titanium alloys over a wide range of strain rates and temperatures. Other kinds of phenomenological constitutive models including Khan–Huang–Liang [23], Johnson–Cook [24], Fields-Backofen [25] and mechanical threshold stress [25] models are also found applications in the modelling of flow behaviour of titanium alloys at elevated temperatures. Liu et al. [26] found that the high temperature flow stress of Ti17 titanium alloy could be predicted accurately by using a developed multivariate nonlinear regression model, and the average relative error between the predicted values by the developed empirical model and experimental results could be controlled within 5.42%. Our previous study indicated that an empirical multiple-linear regression method could be used to model the flow behaviour of hydrogenated Ti–6Al–4V alloys in the β phase field with high accuracy [27].

The accuracy, however, is usually not high enough in some cases in the modelling of flow behaviour by using both the phenomenological and empirical models due to their lack of physical background [28]. Artificial neural network (ANN) modelling is a powerful alternative approach to deal with a series of complicated problems such as non-linear systems and unknown data prediction [29]. ANN requires little knowledge of the physical background of the processes, and can dramatically benefit the industry [30]. ANN has found a variety of applications in many aspects of materials science including prediction of hot deformation behaviour [31,32], generation of processing maps for hot working processes [33] and modelling of the processing–microstructure–property relationships [34].

Ti600 alloy is a recently developed near-α high-temperature titanium alloy which can serve stably at the temperature up to 600 °C due to its characters of excellent creep performance, high tensile strength and good fatigue resistance at the serving temperature [35]. Ti600 alloy is particularly suitable for the manufacture of aerofoil blades and discs in the aviation and aerospace industries. From the perspective of industrial production, hot deformation is a very important operation employed to modify the required final microstructure and mechanical properties of Ti600 alloy. Even though a lot of studies have been conducted on the rolling processes [36], hot deformation behaviours [18,37], fatigue resistance [38] and creep properties [39], there is still a lack of systematic study on the modelling of the hot deformation behaviour of Ti600 alloy by using ANN and as well as phenomenological and empirical models in order to obtain the optimum processing conditions.

In the current work, a comparative study has been made on the performance of phenomenological, empirical and ANN methods in modelling the hot deformation behaviour of Ti600 alloy. The objective of this work is to find out a suitable approach to model the flow behaviour of Ti600 alloy during hot deformation based on the data obtained from hot compression tests. The hyperbolic sine Arrhenius-type phenomenological and multiple-linear regressed empirical models were employed to establish the constitutive equations. An ANN model was developed to predict the flow stress of Ti600 alloy as a function of strain, strain rate and temperature. The performance of these models was evaluated in terms of correlation coefficient, mean absolute relative error and root mean square error. The work will benefit the practical production of Ti600 alloy by optimising the hot working conditions.

2. Experimental procedure

The material used in this investigation was a forged Ti600 titanium alloy. It was supplied as cylindrical specimens with diameter of 8 mm and height of 15 mm by Beijing Aeronautical Manufacturing Technology Research Institute, China. The chemical compositions in weight percentage are as follows: Al 6, Sn 2.8, Zr 4, Mo 0.5, Si 0.4, Y 0.1, and balanced Ti. Hot compression tests were performed on a Gleeble-1500D thermo-mechanical test simulator at temperatures of 760, 800, 840, 880 and 920 °C with strain rates of 0.01, 0.1, 1 and 10 s^{-1}. In order to minimise the friction and barrel development during deformation, and to prevent bonding of the specimens to the anvils, graphitic lubricant was applied to the mating surfaces. The specimens were first heated to the deformation temperatures at a rate of 10 °C/s and held for 3 min, and then compressed up to a maximum true strain of 0.7. No significant barrelling was observed in the compression tests. The tested specimens were immediately quenched in water after deformation. The schedule for hot deformation tests is schematically illustrated in Fig. 1.

Disc samples with a diameter of 3 mm were used for transmission electron microscope (TEM) investigations. The TEM samples were prepared by electro-polishing in an electrolyte of "6 vol.% $HClO_4$ + 34 vol.% C_4H_9OH + 60 vol.% CH_3OH" with temperature of −40 to −35 °C, voltage of 50–55 V and current of 30–35 mA. TEM observations were carried out on a TECNAL G^2 20 microscope operated at 200 kV.

3. Results and discussion

3.1. Flow behaviour

Fig. 2 shows the flow stress curves obtained from the hot deformation tests of Ti600 alloy. The general characteristics of the flow stress curves are similar at all deformation conditions, i.e. all the curves exhibit a dynamic softening phenomenon after a peak stress with an increase of strain. Flow softening of Ti600 alloy during compression is known to occur due to the deformation heating and microstructural evolution such as DRX and spheroidisation

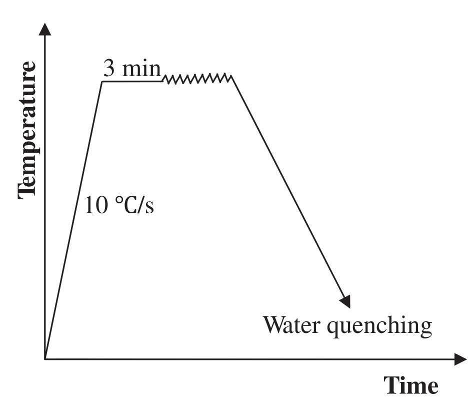

Fig. 1. Schematic illustration of the schedule for hot deformation tests.