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Prediction of hot compression flow curves of Ti–6Al–4V alloy in $\alpha + \beta$ phase region

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ABSTRACT

Prediction of material flow behavior is essential for designing the forming process of any material. In this research, experimental flow curves of Ti–6Al–4 V alloy were obtained using the isothermal hot compression test done at 750–950 °C with 50 °C intervals and constant strain rates of 0.001, 0.005 and 0.01 s^{-1}. For prediction of hot deformation flow curves two methods of modeling were applied. In the first method, an entire flow curve was modeled using Sellars equation. In the second one, modeling of a flow curve up to the peak point was carried out with Cingara model, and modeling beyond that was performed with a model developed based on the Johnson–Mehl–Avrami–Kolmogorov (JMAK) theory. The accuracy of each model was examined through a statistical method. Results showed that flow curve modeling using Cingara model and JMAK theory leads to results that are more consistent with the experimental data.

1. Introduction

Owing to an excellent combination of high specific strength and toughness along with excellent corrosion resistance, Ti–6Al–4 V alloy is the most common titanium alloy in aerospace application, pressure vessels, turbine blades, surgical implants, etc. [1,2]. During hot forming processes, the material experiences a complex combination of strain, strain rate and temperature modes. Therefore, understanding material flow behavior is of great importance for designing hot working processes. Modeling of the hot deformation flow behavior of metals and alloys has been investigated extensively.

Constitutive equations used to determine hot working constants and activation energy of deformation, like power law and hyperbolic sine equations, may be applied for modeling the hot deformation flow behavior of materials [3,4].

Empirical models such as Johnson–Cook and Zerilli–Armstrong models express flow stress as a function of hot deformation variables such as strain, strain rate and temperature [5,6]. Since these models are convenient to use, they are utilized in finite element (FE) codes such as Abaqus and Ls-Dyna softwares.

The artificial neural network (ANN) method provides an efficient alternative approach for modeling the flow behavior of material. An ANN learns from examples and recognizes patterns in a series of input and output values without requiring any information about the mechanism of a phenomenon. Since ANN does not explicitly embed the physical knowledge of deformation mechanisms, it has the ability to predict the flow stress during hot deformation [7,8].

Although hot deformation behavior of Ti–6Al–4 V alloy in either $\alpha + \beta$ or β phase region has been greatly investigated, few researches have been conducted to model the flow behavior of this alloy with the microstructural-evolution-based models. The aim of this study is to introduce a reliable method for modeling the flow behavior of Ti–6Al–4 V alloy. In this regard, the experimental flow curves obtained from isothermal hot compression tests are modeled using two methods. In the first method, an entire flow curve was modeled using Sellars equation. In the second one, modeling of a flow curve up to the peak point was carried out with Cingara model, and modeling beyond that was performed with a model developed based on the Johnson–Mehl–Avrami–Kolmogorov (JMAK) theory. The reliability of each model is evaluated by calculating the root mean square error (RMSE); then, a reliable model is identified.

2. Experimental procedure

For this study, a commercial grade Ti–6Al–4 V alloy with the chemical composition given in Table 1 was used. Cylindrical specimens with diameter of 7.5 mm and height of 12 mm were prepared. All specimens were homogenized at 1100 °C for 25 min and then air cooled to the ambient temperature to obtain fully lamellar microstructure.

After the homogenization process, isothermal compression tests were carried out at 750–950 °C with 50 °C intervals and constant strain rates of 0.001, 0.005 and 0.01 s^{-1}. The experiments were terminated when the true strain of 0.8 was achieved. In Fig. 1, the processing route used in this study is summarized. As

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Table 1
Chemical composition of Ti–6Al–4 V alloy.

Element	Al	V	C	Fe	Pb	Cu	Sb	Bi	Ni	Mn	Zn	Ti
wt.%	6.7	4.5	0.07	0.72	0.1	0.04	0.04	0.05	0.014	0.011	0.003	87.792

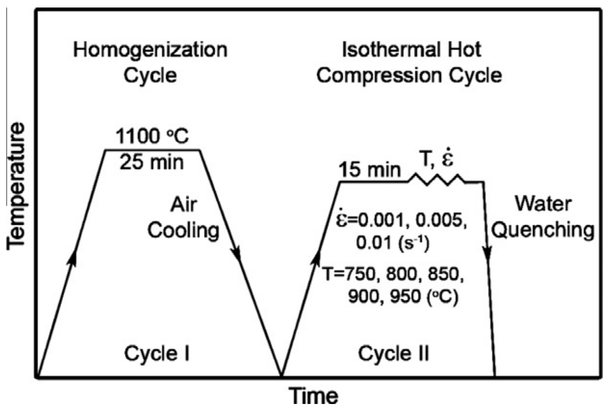

Fig. 1. Processing route for isothermal hot compression test.

the β transus, which depends on the interstitial element content [9], for Ti–6Al–4 V alloy is in the range of 980–1020 °C [10], the experiments were performed in the $\alpha + \beta$ phase region.

Isothermal compression tests were conducted using computer-controlled Instron 8503 material testing system. Fig. 2 shows the experimental set up used in this research. A resistance furnace was used to surround the platens and specimens. The temperature of the specimens was monitored using a K-type thermocouple. Thin mica disks were used at the top and bottom surfaces of the test specimens to reduce the friction involved in the compression test. To avoid high temperature oxidation of apparatus and specimens, the atmosphere of the furnace was controlled by blowing a stream of the inert gas, Ar, throughout the experiments.

3. Results and discussion

3.1. Experimental results

Fig. 3 shows true stress–true strain curves obtained in this study for isothermal compression tests at different temperatures and strain rates.

According to Fig. 3, each flow curve exhibits a single peak point at relatively low strains which are followed by flow softening in larger strains. The appearance of the peak stress and steady state stress in flow curves indicates that the dynamic recrystallization (DRX) phenomenon is the dominant restoration mechanism during hot deformation of Ti–6Al–4 V alloy [11]. From the beginning of the isothermal compression test, flow stress continuously increases due to strain hardening, resulted from increasing dislocation density of the deforming material. DRX consumes stored strain energy and generates new, dislocation free grains.

As a result of decreasing dislocation density due to DRX, the material gradually undergoes flow softening. Since all the applied strain rates were less than 1 s^{-1}, adiabatic heat generation during deformation process has negligible effect on the flow softening behavior [12–14]. Competition between two simultaneously occurring phenomena, strain hardening and flow softening, appears as a peak point and plateau in the flow curves. The peak points in the flow curves indicate that the flow softening is faster than the strain hardening. On the other hand, the equilibrium in hardening and softening phenomena results in a steady state flow behavior, illustrated by a plateau in flow curves [15].

Typical microstructures of hot deformed specimens at different strain rates and temperatures are shown in Fig. 4. As evident from Fig. 4a–d, the morphology of the α lamellar structure is modified due to the globularization mechanism. During the hot working process, the break-up of the prior α lamella occurs, and the metastable Widmanstätten structure converts to a more stable, equiaxed configuration. Comparison of the microstructures shown in Fig. 4a and b as well as Fig. 4c and d reveals that the globularization at lower temperatures and higher strain rates resulted in the finer α particles.

According to Weiss et al. [16], the dynamic globularization mechanism involves two steps: formation of sub-boundaries across α lamellae and separation of the sub-grains. Two possible processes may lead to formation of sub-boundaries. During deformation process, the α lamellae can accumulate a relatively high dislocation density. Simultaneous dynamic recovery, which is a faster softening process than the dynamic recrystallization, results

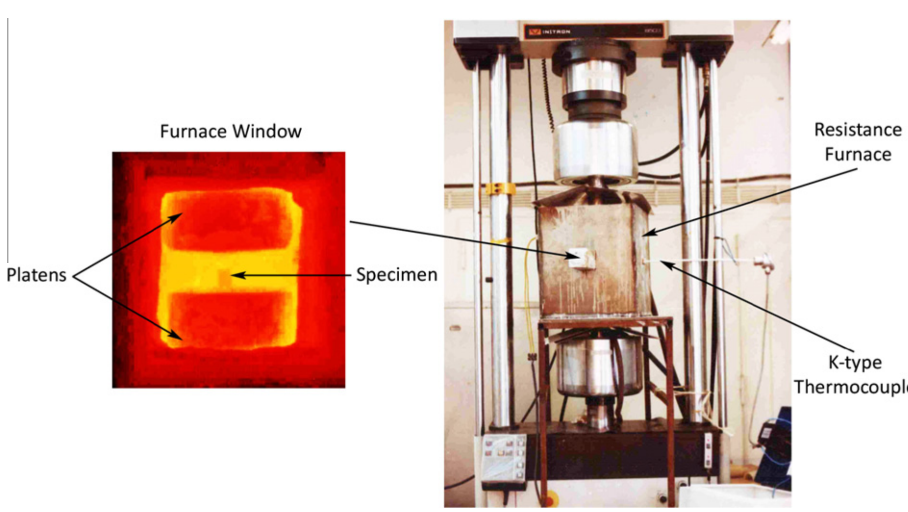

Fig. 2. Instron 8503 material testing machine and adjunct apparatus used for hot compression test.