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Microstructural evolution and constitutive models to predict hot deformation behaviors of a nickel-based superalloy

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ABSTRACT

To investigate the hot deformation behaviors of a nickel-based superalloy, the hot compressive tests are conducted at the deformation temperature range of 920–1040 °C and strain rate range of 0.001-1s^{-1}. It is found that the effects of strain rate and deformation temperature on the grain boundary maps are significant. An almost competed dynamic recrystallization (DRX) microstructure occurs at relatively low strain rates. However, the increased strain rate easily leads to the uneven microstructures. The DRX degree notably increases with the increase of deformation temperature, because the high temperature enhances the grain boundary migration mobility and facilitates the nucleation and growth of DRX grains. Based on the experimental results, multi-gene genetic programming (MGGP), artificial neural network (ANN) and Arrhenius type phenomenological models are established to predict the flow stress. Due to the obvious over-fitting problem of MGGP model, a Hannan-Quinn information criterion based MGGP (HQC-MGGP) approach is proposed. The performances of MGGP, HQC-MGGP, ANN and phenomenological models are compared. It is found that HQC-MGGP model has the best performance to predict the flow stress under the experimental conditions. Therefore, HQC-MGGP model is accurate and reliable in describing the hot deformation behaviors of the studied nickel-based superalloy.

1. Introduction

Due to its high specific stiffness, corrosion resistance and mechanical properties at relatively high temperature, nickel-based superalloys are widely used in advanced turbine engines and nuclear parts. The previous studies show that the hot deformation behaviors of nickel-based superalloys are very complicated [1–5]. Not only the hot deformation parameters, but also the initial microstructures affect the hot deformation behaviors and final properties [6–12]. So, it is crucial to investigate the hot deformation behaviors for optimizing the forming process of nickel-based superalloys.

Generally, hot deformation is an effective method for shaping metals and alloys, which contains lots of typical metallurgical behaviors and markedly relates to the deformation parameters, including strain, strain rate and deformation temperature [13–17]. In order to precisely simulate for hot deformation processes, various constitutive models have been established or modified [18]. These models can be classified into phenomenological, physically-based and artificial neural network (ANN) models [18]. Arrhenius type equation is one of the phenomenological models. Lin et al. [19] improved the Arrhenius model by compensations of strain and strain rate to characterize the hot deformation behaviors of 42CrMo steel. Similarly, some modified Arrhenius models were utilized to characterize the flow behaviors of some aluminum alloy [20–24], alloy steels [25–27], Ni-based superalloys [28,29], magnesium alloys [30,31], and titanium alloys [32,33]. Based on dislocation evolution theories, physically-based models are used to characterize hot deformation behaviors of typical alloys [34–42]. However, the material constants of physically-based and phenomenological models are often obtained by regression method, which needs plenty of experiments and complex calculations. In addition, the calculated material constants are only available in limited experimental conditions, which seriously restrain

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the application of those constitutive models in industrial production. ANN model, which is an artificial intelligence method, can be easily established to describe the hot deformation behaviors of metals and alloys [43–45]. However, the performance of ANN model largely depends on the proper parameters settings, and the definite expression for the hot deformation behaviors cannot be presented by ANN model [18].

In contrast, genetic programming (GP) model, which can automatically evolve and return a definite mathematical expression [46,47], may be a good method to characterize hot deformation behavior of alloys. The framework of GP is almost the same as that of genetic algorithms (GA). However, the differences between these two methods are that GA returns a string of binary or real numbers, whereas, a tree structure is presented as solution for GP. Recently, multi-gene genetic programming (MGGP) [48,49], has received an increasing attention. Unlike GP, the MGGP model is randomly combined by several sets of genes/trees, which means that the MGGP model has better capabilities of evolution and generalization than GP model. However, the over–fitting [50] problem is inevitably existed in the MGGP model, which means this model can only capture the relationships of training data instead of the whole studied objects. So, some researchers presented several heuristics and methods to tackle the over–fitting problem. Garg et al. [51] improved the standard MGGP algorithms to avoid over–fitting problem, and established a suitable constitutive model for 304 austenitic stainless steel.

In this study, the hot deformation behaviors of a typical nickel–based superalloy are researched by high temperature compressive testes. Based on the experimental results, the MGGP, ANN and Arrhenius type phenomenological models are applied to predict the flow stress. In order to overcome the over-fitting problem of MGGP model, a Hannan-Quinn information criterion based MGGP (HQC-MGGP) model is proposed. Finally, the performances of MGGP, HQC–MGGP, ANN and Arrhenius type phenomenological models are compared.

2. Materials and experiments

A commercial nickel-based superalloy was used in this study with the chemical composition (wt.%) of 52.82Ni-18.96Cr-5.23Nb-3.01Mo-1.00Ti-0.59Al-0.03C-0.03Co-(bal.)Al. The cylinder specimens with dimensions of Ø8 mm × 12 mm were prepared from the forged bar. Before compression, the specimens were rapidly heated to 1040 °C and held for 45 min for solution treatment, then followed by water quenching. A Gleeble 3500 machine was used to conduct the hot compressive tests. Generally, the forming temperatures of the studied nickel-based superalloy can be selected from 940 to 1120 °C [1,8,34,52–54]. So, the temperatures were selected as 920, 950, 980, 1010 and 1040 °C. The strain rates were chosen from 0.001 to 1 s^{-1}. Firstly, the specimen was heated up to designed deformation temperature with the heating rate of 10 °C/s and held for 300 s. Next, the compressive tests were conducted, and the deformation degree of specimen reduction was 70%. For minimizing the friction, tantalum foils were used to lubricate the dies and specimen. Finally, the specimen was immediately quenched by cold water, and the delay time between unloading and quenching was less than 2 s.

The microstructures of specimens were studied by electron backscatter diffraction (EBSD). The detail method for the preparation of EBSD samples can be found in the authors' previous work [55]. A JEOL-7001F1 scanning electron microscope was employed to perform EBSD experiments. The grain boundary maps were obtained using HKL Channel 5 software.

3. Results and discussions

Because of the inevitable existence of interfacial friction between dies and specimen, the deformation of specimens is inhomogeneous, and the final shape reveals an irregular barrel shape. So, the obtained flow curves were overestimated and should be corrected [56,57]. In the authors' previous work, the flow stress has been corrected by the bulge correction factor method [34]. Fig. 1 shows the typical flow stress curves. Generally, it can be divided into three stages, including work hardening, softening and relatively steady stages [58,34]. In the work hardening stage, owing to the rapid multiplication of dislocations, the work hardening rate is relatively high, and the recovery mechanism is inadequate to balance work hardening. In consequence, the flow stress rapidly increases at the beginning of hot deformation. In the softening stage, because of the onset of dynamic recrystallization (DRX), the slope of flow curve starts to decrease, and work hardening behavior is gradually weakened until the peak stress appears. After the peak strain, the flow stress gradually decreases with the further deformation. At last, the flow stress reaches a relatively steady stage when work hardening and dynamic softening reach an equilibrium state.

Also, Fig. 1a obviously reveals that the flow stress is relatively small at low strain rates. This is because the DRX mechanism is enhanced with the decrease of strain rate. Fig. 2 shows the effects of strain rate on the grain boundary maps. Here, the high angle gain boundaries (HAGB) and low angle gain boundaries (LAGB) are denoted by black and gray lines, respectively. Meanwhile, the initial grains and DRX grains are marked. Comparing the initial microstructures before and after hot deformation (Fig. 2a), it is obvious that an almost competed DRX microstructure occurs at relatively low strain rates, as shown in Fig. 2b. However, the microstructure becomes more and more uneven with the increase of strain rate (Fig. 2c and d), which indicates that the percentage of DRX grains is significantly reduced. For the studied superalloy, the primary nucleation mechanism is discontinuous dynamic recrystallization (DDRX), which is induced by local bulging of initial grain boundaries [53]. Although high strain rate can enhance the nucleation of DRX, it is widely accepted that high strain rate can retard the growth of DRX nuclei. Thus, at relatively high strain rate, the DRX-induced dynamic softening is slight and flow stress is large. Fig. 1b shows that the flow stress increases with the decrease of deformation temperature. This is mainly related to the intense softening induced by DRX at relatively high deformation temperatures. Figs. 3 and 2b illustrate the effects of deformation temperature on grain boundary maps. As shown in Fig. 3a, a mixed structure of elongated grains and fine DRX grains can be observed at 920 °C (Fig. 3a). When the deformation temperature is increased to 980 °C, many elongated grains disappear, and the microstructure is gradually replaced by the fine DRX grains (Fig. 2b). With the further increase of deformation temperature, a homogeneous microstructure is visible (Fig. 3b), which indicates that the DRX degree notably increases with the increase of deformation temperature. This is because hot deformation can be considered as thermal process, which is sensitively related to the change of deformation temperature. On the one hand, the obstructions of dislocation motion and crystal slip become easy due to the increased average kinetic energy of atoms at relatively high deformation temperatures [53]. On the other hand, the high temperature enhances the grain boundary migration mobility, which facilitates the nucleation and growth of DRX grains. So, the DRX is accelerated, and the flow stress decreases [59–61].