Materials Science & Engineering A 662 (2016) 54–64

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Unified modeling of flow behavior and microstructure evolution in hot forming of a Ni-based superalloy

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ARTICLE INFO

Article history:
Received 30 January 2016
Received in revised form
8 March 2016
Accepted 10 March 2016
Available online 11 March 2016

Keywords:
Unified constitutive model
Flow behavior
Microstructure evolution
Ni-based Superalloy

ABSTRACT

In this paper, the flow behavior and microstructure evolution of a Ni-based superalloy were investigated by hot compression tests with true strain between 0.223 and 0.916, strain rate between 0.001 and 1 s^{-1} and deformation temperature between 1223 and 1373 K. Based on the experimental results, a set of internal-state-variable based unified constitutive equations were proposed to model the flow stress and microstructure evolution of the studied superalloy. The evolution models of dislocation density, average grain size, and dynamic recrystallization fraction were developed and embedded into the constitutive law, which was derived from thermal activation theory and composed of athermal and thermal stresses. The proposed model was calibrated using experimental flow stress and dynamic recrystallization fraction. The predicted flow stress and dynamic recrystallization fraction under different deformation conditions agreed well with the experimental results. Additionally, flow stress under step-strain rate condition was also precisely predicted by the model. The contributions of long and short range barriers to the overall flow stress, variation of corresponding stress components, and microstructure evolution with strain were further analyzed using the unified model. The thermal stress only varied with deformation temperature and strain rate, while the grain boundary strengthening component and stress contribution of dislocation interactions varied with the evolution of grain size and dislocation density, respectively.
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1. Introduction

During hot forming processes, materials undergo severe plastic deformation and microstructure changes dynamically. Understanding and modeling the deformation behavior and microstructure evolution such as work hardening (WH), dynamic recovery, static recrystallization (SRX), and dynamic recrystallization (DRX) are crucial to obtaining accurate simulation of hot forming process. Comparing with phenomenological model, the physically-based internal state variable (ISV) material model including relevant underlying microscale deformation mechanism is capable of predicting the deformation behavior more accurately outside the calibration range [1]. Such model with predictive capabilities can be used to optimize process parameters to produce a part that meets all strength and microstructural requirements and shortens the design period [2]. Therefore, it is necessary to develop a physically-based ISV constitutive model to describe deformation behavior and dominant microstructure evolution.

The physically-based ISV methods have been growing in its influence over the past decades [3], and many research have been devoted to formulating a physically-based ISV material model of plastic deformation. Earlier, research [4–8] mainly focused on modeling the WH and dynamic recovery processes, dislocation density is introduced as the ISV to the material model. These works were later extended and developed to describe more complex material mechanisms, such as DRX [1,2,9,10–12], globularization [13,14], precipitation hardening [15,16] and ductile damage [17,18]. During hot forming processes, materials often suffer severe plastic deformation, and the occurrence of DRX would lead to significant microstructure evolution, then give arise to dramatic decrease in the mean flow stress. So it is important to include DRX into the constitutive model. In the past few years, a number of important theoretical advances have been made to incorporate DRX into the constitutive model. For example, Busso [9] proposed a visco-plastic constitutive theory to describe microstructure evolution caused by DRX and grain growth, which relies on scalar ISVs explicitly linked to intrinsic microstructural length scales. Lin et al. [10] proposed a mechanism-based unified visco-plastic constitutive model to characterize the flow behavior, dislocation density, recrystallization and grain size during and after hot deformation. Cram et al. [11] developed a nucleation model considering dynamically evolving substructure size for discontinuous

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http://dx.doi.org/10.1016/j.msea.2016.03.044
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dynamic recrystallization (DDRX), and the model has been coupled with polyphase plasticity and grain growth models to predict the macroscopic stress and grain size evolution during straining. Recently, Fan and Yang [12] proposed an ISV based self-consistent constitutive model, which allows the unified prediction of both flow stress and microstructure evolution during hot working of wrought two-phase titanium alloys in both single-beta region and two-phase region, and the Mecking and Kocks relationship for the evolution of dislocation density was modified to capture the effect of DRX on dislocation density evolution. Brown and Bammann [2] modified a phenomenological plasticity model to describe the evolution of SRX and DRX by integrating ISVs that represent dislocation density and spacing between geometrically necessary subgrain boundaries. Liu et al. [1] developed a unified ISV material model for inelastic deformation in SS304 by explicitly integrating microstructure evolution into a constitutive law.

Ni-based superalloys are extensively used for critical parts of modern gas turbines and aero engines due to their excellent properties [19]. The components for these applications, which are generally made through hot forming, have strict requirements in terms of microstructure and mechanical properties. Their properties are highly sensitive to the processes parameters such as forming temperature, strain rate, and deformation degree. Therefore, it is significant to investigate and model the hot deformation behavior and microstructure evolution of Ni-based superalloys, and then optimize the process parameters through simulation to satisfy the requirements of the components. Numerous studies were conducted to model the hot deformation behavior and microstructure evolution of Ni-based superalloys. Most researchers developed or improved the phenomenological model. For example, Shen et al. [20] employed the Avrami equation to model the DRX and meta-DRX of Waspaloy. Wang et al. [21] investigated the flow behavior and microstructure of superalloy 718, and had a conclusion that the dependence of the peak stress on deformation temperature and strain rate can be expressed by a hyperbolic-sine type equation. Yang et al. [22] designed a novel isothermal compression test to simulate the flow behavior of GH4169 superalloy during linear friction welding and used a strain-compensated Arrhenius type constitutive equation to characterize the deformation behavior of GH4169 superalloy. Bruni et al. [23] modeled the flow behavior of NIMONIC 115 alloy by means of an equation that relates the hyperbolic sine of flow stress to the temperature-modified strain rate. Wu et al. [24] studied the hot deformation characteristics of Inconel 600 superalloy at elevated temperatures, and established a constitutive equation through a simple extension of the hyperbolic sine constitutive relation. In order to describe the effect of evolving microstructures on flow stress response to the deformation of Inconel 718, Zhao et al. [25] modified the DRX model, which was described using the Avrami relationship by incorporating the dislocation density into the Avrami parameter, afterward, dislocation density, DRX fraction, and grain size were introduced as ISVs into a visco-plastic constitutive model. Recently, Lin et al. [19] proposed a two-stage constitutive model for a Ni-based superalloy, DRX kinetics modeled by the Avrami equation, was used to describe the flow softening behavior on the basis of relationship of DRX fraction to flow stress. Although the flow behavior and microstructure evolution of Ni-based superalloys have been widely investigated, much less attention has been paid to the development of sound and physically-based ISV constitutive model, which is able to describe flow behavior and microstructure as well as their interactions.

This work aims to develop a set of unified constitutive equations for a Ni-based superalloy by using the physically-based ISV method. The paper is organized as follows: first, the flow behavior and microstructure evolution of a Ni-based superalloy under hot compression conditions were investigated. Based on the experimental results, a set of unified constitutive equations incorporating Hall-Petch effect, dislocation interaction, and softening of DRX were then developed to predict the flow stress and microstructure evolution of the studied superalloy. Then a genetic algorithm-based optimization method was employed to calibrate the model by using experimental flow stress and DRX fraction. Finally, comparisons between predicted and experimental results were provided, and the unified constitutive model was utilized to analyze the stress component variation and the microstructure evolution.

2. Experimental procedure and results

2.1. Experimental procedure

Table 1 lists the chemical composition of the studied superalloy. Cylindrical test specimens with a diameter of 8 mm and a length of 12 mm were machined from as-received wrought billet. All the specimens were solution treated at 1373 K for 1 h, then followed by water quenching. The microstructure of the studied superalloy before deformation is composed of equiaxed grains with a mean size of 135 μm, which is shown in Fig. 1. Hot uniaxial compression tests were carried out on a Gleeble 1500D thermo-mechanical simulator. Tantalum foils, with a thickness of 0.1 mm were used to reduce friction between the specimens and dies. Prior to isothermal compression, the specimens were heated to the deformation temperature at a heating rate of 10 K s^{-1} and held for 3 min. Compressions were conducted at temperatures of 1223 K, 1273 K, 1323 K, and 1373 K, strain rates of 0.001 s^{-1}, 0.01 s^{-1}, 0.1 s^{-1}, and 1 s^{-1}, and true strains of 0, 0.223, 0.511, and 0.916. Furthermore, two strain rate jump tests were also carried out. The initial strain rates were 0.01 s^{-1} and 0.1 s^{-1}, after compression to a true strain of 0.45, the strain rates increased from 0.01 s^{-1} to 0.1 s^{-1} or decreased from 0.1 s^{-1} to 0.01 s^{-1}. The test was continued until the strain reached 0.9. After hot compression, the specimens were immediately quenched by water to retain the microstructures. The specimens were sectioned along the axial direction for microstructure analysis. After mechanical polishing and etching in a solution consisting of HCl (50 mL)+CH_3CH_2OH (50 mL)+$CuCl_2$ (2.5 g) at room temperature for 5–10 min, the exposed surfaces were observed using an optical microscope. Image Pro-Plus software 6.0 was used to measure DRX fraction and recrystallized grain size in four measurement points and four visual fields in every measurement point at the section center of each specimen.

2.2. Experimental results

Fig. 2 shows the typical true stress-strain curves of the studied superalloy obtained under different deformation conditions. All existing flow curves exhibit pronounced stress peaks, this finding indicates that deformation involves simultaneous hardening and softening as a result of dislocation storage and annihilation, respectively. Obviously, the flow stress decreases with increasing deformation temperature and reducing strain rate. Deformation at high strain rates leads to increased rate of dislocation generation. On the other hand, high temperatures stimulate the dislocation

Table 1
Chemical compositions of the studied superalloy (wt%).

C0.025	Si0.08	Mn0.05	Cr18.02	Ni53.73
Nb 5.40	Mo 2.88	Ti 1.00	Al 0.50	Fe Bal.

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