Computational Materials Science 122 (2016) 150–158

Contents lists available at ScienceDirect

Computational Materials Science

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

A new method to establish dynamic recrystallization kinetics model of a typical solution-treated Ni-based superalloy

Ming-Song Chen [a,b,*], Y.C. Lin [a,b,c,*], Kuo-Kuo Li [a,b], Ying Zhou [a]

[a] School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China
[b] State Key Laboratory of High Performance Complex Manufacturing, Changsha 410083, China
[c] Light Alloy Research Institute of Central South University, Changsha 410083, China

ARTICLE INFO

Article history:
Received 14 February 2016
Received in revised form 8 May 2016
Accepted 15 May 2016

Keywords:
Dynamic recrystallization
DRX kinetics model
DRX volume fraction
Ni-based superalloy
Microstructure

ABSTRACT

The dynamic recrystallization (DRX) behavior of a typical solution-treated Ni-based superalloy is investigated by hot compressive tests and metallographic observations. The DRX volume fractions of deformed specimens are evaluated based on optical micrographs. Results show that the DRX volume fraction and grain size increase with the increase of deformation temperature or the decrease of strain rate. It is found that the method to calculate the DRX volume fraction based on true stress–strain curves is not suitable for the studied superalloy. i.e., the relationships between the DRX volume fraction and strain are hard to obtain. It results in the lack of adequate experimental data to establish the DRX kinetics model by the conventional method. Therefore, a new method, in which only the DRX volume fractions in the center part of deformed specimens need to be employed, is proposed. Considering the friction-induced inhomogeneous deformation in specimens, the values of strain and strain rate in the center part of deformed specimens are obtained by finite element simulation. The material constants of DRX kinetics model are determined by the least square method. An agreement between the predicted and experimental results shows that the established model can well describe the DRX behavior of the studied superalloy.

1. Introduction

Microstructural evolution of metals or alloys is often very complex during hot deformation [1–3]. Complex microstructural evolution mechanisms, including work hardening (WH), dynamic recovery (DRV) and dynamic recrystallization (DRX), often occur in the metals or alloys with low stacking fault energy [4–6]. Besides, the static [7–11] and metadynamic recrystallizations [12,13] also take place in the multi-pass hot deformation process. It is well known that DRX is one of the most important microstructural evolution mechanisms, which can refine initial coarse grains and improve mechanical properties [14–16]. Therefore, understanding the DRX behaviors of metals and alloys is very significant.

DRX kinetics model, which describes the relationships between the DRX volume fraction and strain, strain rate and deformation temperature, is essential to control the microstructures of forgings. In recent decades, some efforts have been made on the DRX behaviors and kinetics models of various metals and alloys [17–47]. Beladi and Hodgson [17] investigated the effect of carbon content on the DRX kinetics of Nb-steels, and found that the DRX depends strongly on thermomechanical parameters, as well as the chemical compositions. Cui et al. [18] studied the DRX behavior of TiAl alloy, and found that the DRX of γ grains is the main softening mechanism. Mirzadeh et al. [19] investigated the DRX behavior of a 304 H austenitic stainless steel by the electron backscattered diffraction (EBSD) technique, and found that the recrystallized fraction can be determined from the grain average misorientation distribution based on the threshold value of 1.55°. The influence of initial microstructure on discontinuous dynamic recrystallization (DDRX) of high purity and ultra-high purity austenitic stainless steels was investigated by Wahabi et al. [20]. They concluded that larger initial grain sizes can promote a delay in the DDRX onset in the two alloys. Chen et al. [21] investigated the DRX behavior of 42CrMo steel, and established the DRX kinetics model, in which the effects of initial grain size on the DRX behavior were considered. Based on true stress–strain curves, Lv et al. [22] established the DRX kinetics model of Mg–2.0Zn–0.3Zr alloy. By isothermal compressive tests and metallographic observations, Liu et al. [23] investigated the DRX behavior of 300 M steel, and the Avrami equation was established to determine the DRX kinetics. Mirzadeh

* Corresponding authors at: School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China.
E-mail addresses: chenms18@csu.edu.cn (M.-S. Chen), yclin@csu.edu.cn (Y.C. Lin).

http://dx.doi.org/10.1016/j.commatsci.2016.05.016
0927-0256/

and Najafizadeh [24] studied the DRX softening behavior of a 17–4 PH stainless steel, and found that the Avrami kinetics is suitable for extrapolation of flow curves to higher strains. Jiang et al. [25] investigated the substructure and twin boundary evolution of alloy 617B during DRX, and found that the evolution of substructure and twin boundaries have a significant effect on DRX process. Ning et al. [26,27] studied the DRX behavior and microstructural evolution of the hot isostatic pressed FGH4096 superalloy. Chen et al. [28] presented a two-dimensional cellular automata (CA) approach to predict the microstructural evolution of 316LN austenitic stainless steel during DRX. In addition, the DRX behaviors and kinetics models of 410 martensitic stainless steel [29], titanium-modified austenitic stainless steel [30,31], SCM435 steel [32], 304stainless steel [33,34], X70 pipeline steel [35], 38MnVS6 Steel [36], Cu–0.4 Mg alloy [37], magnesium alloys [38–40], Mg–Y–Nd–Zr alloy [41], Mg-Li-Al–Nd duplex alloy [42], Mg–Gd–Y–Zr alloy [43] and Ti55511 titanium alloy [44] were studied. In the previous reports, the Avrami equation [45] was often used to describe the relationships between the DRX volume fraction and strain at given deformation temperature and strain rate. ε_c (the critical strain for the onset of DRX) and $\varepsilon_{0.5}$ (the strain for 50% DRX), which are the functions of deformation temperature and strain rate [17–47], are the characteristic parameters of Avrami equation. The true stress–strain curves were often used to determine the values of ε_c and $\varepsilon_{0.5}$ at different deformation conditions [46,44,47]. Then, based on obtained ε_c and $\varepsilon_{0.5}$, the material constants of DRX kinetics model were determined by the linear fitting method.

The Ni-based superalloys, typical precipitation strengthened alloys with ultrahigh alloying degree, are widely applied in aerospace and energy industries [48,49]. Over the last decades, some investigations on hot deformation behaviors of Ni-based superalloys have been carried out [48–62]. Based on the true stress–strain data, Lin et al. [49,50], Liu et al. [51], Etaati et al. [52], Yu et al. [53] and Zuo et al. [54] developed the flow stress constitutive equations of typical Ni-based superalloys. Wen et al. [55], Zhang et al. [56] and Zhang et al. [57] established the processing maps to gain the optimum hot deformation domains of typical Ni-based superalloys. Reyes et al. [58] established the grain size model of a Ni-based superalloy using CA algorithm. Kaoumi and Hrutkay [59] found that microstructural evolution of 617 superalloy is significantly influenced by temperature and strain rate under tensile load. Zhang et al. [1,2] studied the effects of strain rate on microstructural evolution of a Ni-based superalloy during hot deformation, and found that the mechanisms for the nucleation of DDRX and CDRX are closely related to strain rate. Chen et al. [60] investigated the DRX behavior of a typical Ni-based superalloy by hot compressive tests, and the segmented models were established to describe the DRX kinetics. Liu et al. [61] studied the DRX kinetics and microstructural evolution by a CA model. Lin et al. [62] investigated the microstructural evolution of hot deformed Ni-based superalloy, and found that DDRX is the dominant nucleation mechanism.

In the paper, the DRX behavior of a typical solution-treated Ni-based superalloy is investigated by hot compressive tests and metallographic observations. A new method is proposed to establish DRX kinetics model. In the new method, the friction-induced inhomogeneous deformation of specimens is considered. The strain and strain rate in the center of deformed specimens are obtained by finite element simulation. The DRX volume fractions are evaluated based on optical micrographs. The material constants of DRX kinetics model are determined based on the DRX volume fractions and strain, strain rate and deformation temperature in the center part of deformed specimens. In addition, for the studied Ni-based superalloy, the feasibility to evaluate the DRX volume fraction by analyzing the true stress–train curves is discussed.

2. Material and experiments

2.1. Experimental material

The material used in the study is a typical Ni-based superalloy with the composition (wt%) of 52.82Ni–18.96Cr–5.23Nb–3.01Mo–1.00Ti–0.59Al–0.01Co–0.03C–(bal.) Fe. Cylindrical specimens were machined with a size of ϕ10 mm × 12 mm from a forged billet. All specimens were heated to 1040 °C and hold for 45 min in heat treatment furnace, then quenched by water.

2.2. Hot compressive experiments

Hot compressive experiments were done on Gleeble-3500 thermo-mechanical simulator. Five different deformation temperatures (920, 950, 980, 1010 and 1040 °C) and four strain rates (0.001, 0.01, 0.05 and 0.1 s^{-1}) were used in the hot compressive experiments, and the deformation degrees for all specimens are 60%. The tantalum foils with thickness of 0.1 mm were used in order to minimize the friction between the specimen and dies. Before deformation, each specimen was heated to the deformation temperature at a heating rate of 10 °C/s, and then held for 300 s to eliminate the thermal gradient. The true stress–strain data were recorded by the testing system. All deformed specimens were immediately quenched by water.

2.3. Metallography experiments

In order to observe the microstructures, the deformed specimens were cut along the compressive axis section. Then, the compressive axis sections were mechanically polished and etched in the solution of HCl (100 ml) + CH_3CH_2OH (100 ml) + $CuCl_2$ (5 g) at room temperature for 3–5 min. The microstructure was observed by a Leica optical microscope (OM). The initial optical microstructure of the solution-treated specimens is shown in Fig. 1. From Fig. 1, it is found that the δ phase is absolutely dissolved.

3. Results and discussion

3.1. True stress–true strain curves

Fig. 2 shows the typical true stress–strain curves of the studied superalloy under tested conditions. All the curves are corrected to reduce the effects of frictions using the methods in Ref. [63]. It is obvious that the flow stress is sensitive to the deformation temperature and strain rate. It can be found that the flow stress increases with the increase of strain rate or the decrease of deformation temperature. This is because the critical shear stress of dislocation

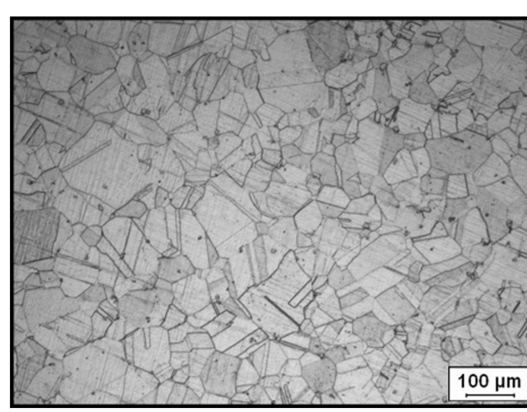

Fig. 1. Initial optical microstructure of specimens after solution treatment.