Materials and Design 57 (2014) 568–577

Contents lists available at ScienceDirect

Materials and Design

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

Dynamic recrystallization behavior of a typical nickel-based superalloy during hot deformation

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ARTICLE INFO

Article history:
Received 26 October 2013
Accepted 28 December 2013
Available online 9 January 2014

Keywords:
Dynamic recrystallization
Nickel-based superalloy
Microstructure
Grain size

ABSTRACT

The dynamic recrystallization (DRX) behavior of a typical nickel-based superalloy is investigated by the hot compression tests. Based on the conventional DRX kinetics model, the volume fractions of DRX are firstly estimated. Results show that there is an obvious deviation between the experimental and predicted volume fractions of DRX when the forming temperature is below 980 °C, which is induced by the slow dynamic recrystallization rate under low forming temperatures. Therefore, the segmented models are proposed to describe the kinetics of DRX for the studied superalloy. Comparisons between the experimental and predicted results indicate that the proposed segmented models can give an accurate and precise estimation of the volume fractions of DRX for the studied superalloy. In addition, the optical observation of the deformed microstructure confirms that the dynamically recrystallized grain size can be well characterized by a power function of Zener–Hollumon parameter.

1. Introduction

During the hot forming of metals or alloys, material flow behaviors are often very complex, and the control of microstructure is of great importance to optimize the final mechanical properties [1–3]. Studies show that the work hardening (WH), dynamic recovery (DRV) and dynamic recrystallization (DRX) often occur in the metals and alloys with low stacking fault energy during the hot deformation [4–6]. For the multi-pass hot forming process, the metadynamic recrystallization [7–9] and static recrystallization [10–12] also occur. Generally, DRX is not only an important softening mechanism, but also an effective method to refine the coarse grain size and reduce the hot deformation resistance. Meanwhile, the mechanical properties of metals and alloys can be improved [1,13,14]. Therefore, it is significant to understand the dynamic recrystallization behaviors of metals or alloys for the optimal processing parameters.

Over the last decades, some efforts have been made on the DRX behaviors of various metals or alloys [15–42]. In order to control the microstructure and mechanical properties, it is essential to quantify the volume fractions of DRX. The Avrami equation [15] is often used to evaluate the softening fractions induced by static recrystallization (SRX), meta-dynamic recrystallization (MDRX) and dynamic recrystallization (DRX). Chen et al. [16] and Quan et al. [17] studied the dynamic recrystallization behaviors of 42CrMo steel during the hot deformation, and the dynamic recrystallization kinetic equations for 42CrMo steel were established. Momeni and Dehghani [18] developed the dynamic recrystallization kinetics models for 410 martensitic stainless steel during the hot deformation. Mandal et al. [19,20] investigated the kinetics, mechanism and modeling of microstructural evolution during dynamic recrystallization in a titanium-modified austenitic stainless steel. The state of stress does not alter the mechanisms of DRX nucleation but hinder the kinetics of DRX during plane-strain deformation [21]. Ebrahimi et al. [22] studied the dynamic recrystallization behavior of a superaustenitic stainless steel containing 16%Cr and 25%Ni, and found that increasing temperature or decreasing strain rate lowers the driving force for DRX. Yin et al. [23] investigated the microstructural evolution of GCr15 steel by physical experiments and finite element method (FEM), and formulated the austenite grain growth and dynamic recrystallization of GCr15 steel by the linear regression method and genetic algorithm. Based on the classical stress-dislocation relation and the kinematics of DRX, the constitutive equations for 42CrMo steel were established by Lin et al. [24]. Also, similar physically-based constitutive models were developed to predict the flow behaviors of N08028 alloy [25] and 7050 aluminum alloy [26]. Zeng et al. [27] studied the hot deformation and dynamic recrystallization behavior of a high Nb containing TiAl alloy, and established the Avrami type equation to predict the volume fractions of DRX. Lin et al. [28,29] investigated the microstructural evolution during DRX in 42CrMo steel, and obtained the general mechanisms of

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0261-3069/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.12.072

DRX. i.e., with the increase of the deformation temperature, the dynamic recrystallization easily occurs and the microstructures become more and more homogenous. But, the grains also easily grow up because of the enhancement of the grain boundary diffusion and migration when the deformation temperature is high enough. Additionally, the dynamic recrystallization behaviors of Cu–0.4 Mg alloy [30], 17-4 PH stainless steel [31], SCM435 steel [32], magnesium alloys [33,34], 304 stainless steel [35,36], Ti-modified 15Cr–15Ni–2Mo austenitic stainless steel [37], as-extruded 7075 aluminum alloy [38], 300M steel [39], as-extruded 3Cr20Ni10W2 heat-resistant alloy [40], 26NiCrMoV 14-5 steel [41], 3Cr2NiMnMo steel [42], and cast A356 aluminum alloy [43] were studied.

The nickel-based superalloy, one typical precipitation strengthened steel, is widely used in modern aero engines and gas turbine. The strengthening mechanism is mainly ascribed to the coherent γ' (LI_2 structure with Ni_3 (Al, Ti) composition) and γ'' (DO_{22} structure with Ni_3Nb composition) phases in the face centered cubic matrix (γ phase) [44,45]. The γ'' phase is usually unstable. It can be transformed to the equilibrium δ phase (Ni_3Nb). The δ phase can also directly precipitate from the supersaturated solid solution when the temperature is higher than 750 °C [46]. Due to the different precipitation phases, together with their changeable shapes and distributions, the hot deformation behaviors of nickel-based superalloys are generally complex. In recent years, some investigations on the hot deformation behaviors of nickel-based superalloys have been carried out [47–59]. Li et al. [47] and Guo et al. [48] studied the microstructural evolution of Inconel 625 superalloy, and confirmed that the continuous dynamic recrystallization (CDRX) is the main softening mechanism at the early deformation stage; while the discontinuous dynamic recrystallization (DDRX) plays a dominant role at the later deformation stage. Wang et al. [49] discussed the microstructural evolution of superalloy 718 during the hot deformation, and found that the nucleation mechanisms for DRX are significantly affected by the deformation temperature. Wen et al. [50] and Cai et al. [51] investigated the hot deformation behaviors of typical Ni-based superalloys, and established the processing map to optimize the hot working processing for the studied superalloys. Ning et al. [52] studied the hot deformation behavior of the post-cogging FGH4096 superalloy with fine equiaxed microstructure, and developed a phenomenological constitutive model to characterize the dependence of steady flow stress on the forming temperature and strain rate. Also, Ning et al. [53] constructed the processing map for GH4169 superalloy associated with stick δ phase based on the isothermal compression experiments. Based on the stress-dislocation relation and kinetics of dynamic recrystallization, Lin et al. [54] established a two-stage constitutive model to predict the flow stress of a typical Ni-based superalloy (GH4169). Also, Lin et al. [55] studied the hot tensile deformation behaviors and fracture characteristics of a typical Ni-based superalloy (GH4169), and found that the typical DRX characteristics appear under relatively high deformation temperatures (1010 and 1040 °C). Wu et al. [56] studied the hot compressive deformation behavior of a new hot isostatically pressed Ni–Cr–Co based powder metallurgy superalloy. By the finite-element (FE) method, the microstructural evolution of the nickel-based superalloys were also simulated by other researchers [57–59]. Therefore, it can be found that the previous investigations give the profound attention on the hot deformation behaviors, as well as DRX mechanisms of nickel-based superalloys. However, there is still less concern about the evaluation of softening fractions induced by DRX for nickel-based superalloys. Due to the significant effects of DRX on the hot deformation behavior, as well the microstructures and mechanical properties of nickel-based structure parts, it is necessary to accurately estimate the volume fractions of DRX during the hot deformation.

In this study, the DRX behaviors of a typical nickel-based superalloy are investigated by the isothermal hot compression tests. The kinetics equations of DRX for the studied superalloy are developed to describe the dynamic recrystallization behaviors. The validity of the established DRX kinetics equations is confirmed. The effects of the forming temperature and strain rate on the dynamically recrystallized grain size are also discussed.

2. Materials and experiments

The chemical compositions (wt.%) of the studied superalloy are as follows: 52.82Ni–18.96Cr–5.23Nb–3.01Mo–1.00Ti–0.59Al–0.01Co–0.03C–(bal.)Fe. Cylindrical specimens with a diameter of 8 mm and a height of 12 mm were machined from the wrought billet. The specimens were solution treated at 1040 °C for 0.75 h followed by the cold water quenching. Hot compression tests were performed on Gleeble-3500 thermo mechanical simulator. Six different forming temperatures (920, 950, 960, 980, 1010, and 1040 °C) and four different strain rates (0.001, 0.01, 0.1, and 1 s^{-1}) were used in hot compression tests, and the final deformation degree was 70%. In order to minimize the frictions during hot deformation, the tantalum foil with the thickness of 0.1 mm was used between the specimen and dies. Each specimen was heated to the designed forming temperature at a heating rate of 10 °C/s, and then soaked for 300 s to eliminate the thermal gradient before loading. The stress–strain data were automatically recorded by the testing system during the hot compression. The specimens were immediately quenched by the cold water after each experiment. Then, the deformed specimens were sliced along the compression axis section for microstructural analysis. After polished mechanically and etched in a solution consisting of HCl (100 ml) + CH_3CH_2OH (100 ml) + $CuCl_2$ (5 g) at room temperature for 3–5 min, the exposed surfaces were observed by optical microscope (OM). The average grain size was evaluated by the linear intercept method, according to the standard ASTM: E112-12. Fig. 1 shows the microstructure of the studied superalloy before hot deformation. It is observed that the microstructure consists of equiaxed grains with a mean grain size of 75 μm.

3. Results and discussion

3.1. Hot deformation behavior

The true stress–strain curves of the studied superalloy under different forming temperatures and strain rates are illustrated in Fig. 2. It is observed that the flow stress rapidly increases to a peak value, and then gradually decreases to a relatively steady state. It can be found that the flow stress curve is composed of three stages: stage I (work hardening stage), stage II (softening stage) and stage

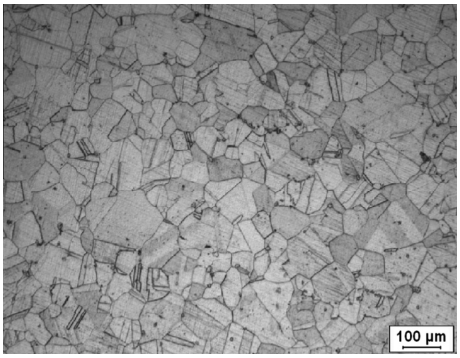

Fig. 1. Optical micrograph of the studied superalloy before hot deformation.