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Evolution of grain refinement degree induced by dynamic recrystallization for Nimonic 80A during hot compression process and its FEM analysis

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ABSTRACT

In order to analyze the evolution of grain size for Nimonic 80A and further controlling the structures and properties of hot deformed parts, a series of isothermal hot compression tests were conducted with the height reduction range of 10%–60% under the strain rate range of 0.01–10 s^{-1} and the temperature range of 1237–1523 K on a Gleeble-3500 thermo-mechanical physical simulator. According to the experimental data, the grain refinement degree was proposed and computed in this work so as to quantitatively analyze the variation of grain size during the whole deformation for Nimonic 80A. The onset strains of DRX initiation (ε_c) were identified by $\theta - \sigma$ curves (strain hardening rates curves) and their derivative. Then the dynamic recrystallization kinetics model and the dynamic recrystallization grain size model were established based on the results from thermo-simulation experiments and metallographic analysis. After that, the grain refinement degrees of the specimens were proposed and calculated, then the effects of temperature, strain rate and deformation degree on the grain refinement degree were discussed through the metallographs over a wide range of temperatures and strain rates. Finally, the developed models were applied in the finite element simulation model, which implies a good application prospect of the theoretical calculation.

1. Introduction

In recent years, a nickel-based superalloy, Nimonic 80A, is widely used for jet engines of aircrafts, gas turbines of power plants, diesel engines of marines, etc., due to its superior properties such as high creep resistance, high yield strength, high-corrosion resistance, and good weldability, etc. [1,2,3]. Currently, the products of Nimonic 80A are usually manufactured by extrusion and forging processes [4,5], in which three metallurgical phenomena including work hardening (WH), dynamic recovery (DRV) and dynamic recrystallization (DRX) (co-exist at a certain time, and one of them is predominant) are exist [6,7]. The interaction effects between those phenomena determine the microstructures and corresponding mechanical properties of deformed material [8,9]. As for the nickel-based alloy with low stacking fault energy, DRX is prone to occur and predominant in strain softening mechanisms resulting in grain refinement [10]. The grain size, as a considerable indicator of microstructure, determines the macro-mechanical properties of materials to a large extent [11,12]. It is a significant issue to investigate how to adjust the microstructures by DRX grain refinement and even control the properties of deformed materials. Moreover, the product's distribution of phases and mechanical properties are largely determined by processing variables, such as temperature, strain rate and true strain. Such parameters are designed and optimized by multi-scale numerical simulation with finite element method (FEM) [9,13]. Consequently, for the products of Nimonic 80A, in order to control microstructure evolution and further insuring mechanical property by regulating process parameters, it is significant to analyze the evolution of grain size by establishing DRX kinetics & grain size model, and further developing their applications with finite element method (FEM).

Over the last few decades, considerable researches have focused not only on detecting and analyzing the phase microstructures of materials which undergo DRX during deformation but also on modelling the DRX kinetics of alloys [14,15]. Wang et al. identified two types of nucleation mechanisms of superalloy 718 according to the microstructure observations by optical microscope and electron backscatter diffraction (EBSD) techniques, and then described the

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DRX nucleation process [16]. Baohui Tian et al. distinguished the microstructures under dynamic recrystallization and dynamic recovery in hot deformed Nimonic 80A via dislocation density and dislocation structure examinations conducted by X-ray line broadening analysis and transmission electron microscopy respectively [17]. Quan et al. measured the average grain size and the percent of fine grain (less than 20 μm) and found that DRX is the dominant softening mechanism for Nimonic 80A [18]. Such works concentrated on recognizing DRX grains and analyzing micro-mechanisms during a hot deformation process. Then the most serious issue is how to apply the theoretical results in practical applications. At present, finite element method (FEM) with thermal-mechanical-microstructure dynamic coupling supplies an effective flat form to program theoretical models into codes conveniently. According to these numerical simulations supported by theoretical results, processing parameters can be designed and even optimized. As for the simulation of recrystallization transformation in any forming process by FEM, abundant and accurate basic material data including stress-strain data and especially DRX kinetics support accurate FEM analysis. Li et al. established mathematical models to predict DRX, DRV and grain size evolution of plastic mold steel (SDP1) [19]. Quan et al. modeled the dynamic recrystallization evolution of Ti–6Al–4V alloy in $\alpha+\beta$-phase temperature range and a wide strain rate range [9]. Such developed kinetics equations were all employed in FEM to predict the microstructure evolution during a thermo-mechanical working process. These works built the DRX kinetics models, but few analyzed the variety of grain size induced by DRX along with processing parameters.

In the present work, a series of compressions of Nimonic 80A alloy with a height reduction range of 10%–60% were performed in the temperature range of 1273–1373 K and the strain rate range of 0.01–10 s^{-1} on a Gleeble-3500 thermo-mechanical simulator. The strain-stress curves were classified into DRV-type and DRX-type, and two characteristic values including the critical strain for DRX (ε_c) and the strain for peak stress (ε_p) were identified by further analyzing of the experimental stress-strain curves. Then the DRX kinetics and DRX grain size equations were established to describe the evolution of the fraction of DRX volume and grain size, such equations were employing to conduct the simulation process in software. The evolution of grain refinement degree affected by deformation temperature, strain rate and deformation strain have been validated through experimental microstructures. In addition, the developed kinetics models were applied into finite element analysis, which gives a potential application of the theoretical calculation.

2. Thermal compression tests

2.1. Experimental procedures

Nimonic 80A is a wrought, age-hardenable nickel-chromium alloy, strengthened by additions of titanium, aluminum and carbon, and developed for service at temperatures exceeded 1088 K(1500 °F). The chemical compositions of Nimonic 80A in this study were given in Table 1. Twenty-two specimens with a diameter of 10 mm and a height of 12 mm were machined from the same forged billet by wire-electrode cutting. The processing routes of thermal treatments and isothermal hot compressions, which has been performed on a Gleeble 3500 thermal mechanical simulator with computer-controlled and servo-hydraulic, are simplified as Fig. 1. The specimens were resistance heated to deformation temperatures with a heating rate of 5 K/s by thermo-coupled-feedback-controlled AC current, and then held at a certain temperature for 180 s. After that, sixteen samples were compressed to the fixed true-strain of 0.916 (the height reduction of 60%) with four different strain rate of 0.01 s^{-1}, 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1} and four different temperatures of 1273 K, 1323 K, 1373 K, 1423 K. In addition, five specimens were deformed with the true-strain of 0.105, 0.223, 0.357, 0.511, 0.693 (height reduction of 10%, 20%, 30%, 40%, and 50%) under the temperature of 1373 K and the strain rate of 1 s^{-1} to reveal the spatial-temporal evolution of microstructure during the compression. The remained one specimen without heating and compressing was considered as the as-received one for the original microstructure.

Table 1
Chemical composition of the studied alloy Nimonic 80A

Chemical composition	Cr	Ti	Fe	Al	Mn	Si	C	S
% by weight	20.87	2.07	1.26	0.68	0.63	0.55	0.069	0.01

After thermal compressing, rapid water quench was employed to ensure a uniform temperature field to retain the microstructure at elevated temperature and decrease the material anisotropy. The true stress-strain ($\sigma-\varepsilon$) curves derived from thermal compression tests under different temperatures and different strain rates for Nimonic 80A are illustrated in Fig. 2. It is found that the stress is significantly sensitive to temperature and strain rate [20], and all the stress-strain curves exhibit a single peak followed by a strain softening stage and a relatively stable stage at high strain region [21]. It is also seen that the flow stress decreases with the increasing temperature for a specific strain rate and generally increases as the strain rate increases for a fixed temperature [22]. The reason lies in the fact that lower strain rate and higher temperature provide a longer time for the energy accumulation and higher mobility at grain boundaries, these result in the nucleation and growth of dynamically recrystallized grains and dislocation annihilation [23].

During the compression process, the variations of stress and strain were monitored continuously by a computer equipped with an automatic data acquisition system. The true stress and true strain were derived from the nominal stress-strain data according to the following formulas: $\sigma_T=\sigma_N(1+\varepsilon_N)$, $\varepsilon_T=\ln(1-\varepsilon_N)$, where σ_T is true stress, σ_N is nominal stress, ε_T is true strain and ε_N is nominal strain [24].

After compression, the specimens were divided symmetrically into two parts by wire cutting, the schematic of section is shown in Fig. 3. Then such sections were polished mechanically and etched in a solution of HCl (100 ml), H_2SO_4 (5 ml) and $CuSO_4$ (5 g) at room temperature for 60 s, following which the microstructure in the center of section (shown in Fig. 3 with "X") was observed by the

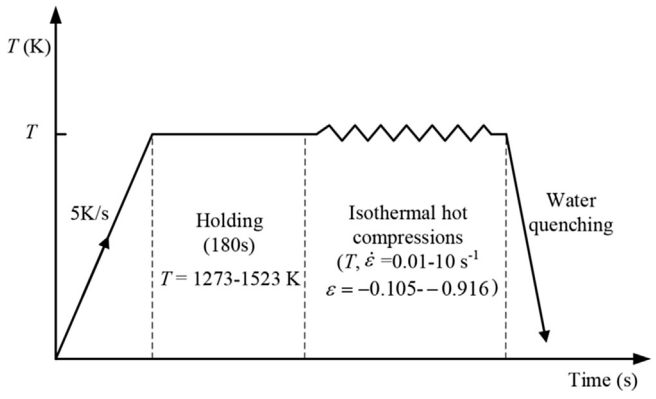

Fig. 1. Processing route for isothermal hot compression test.