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A physically-based constitutive model for a typical nickel-based superalloy

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ABSTRACT

Due to their excellent properties, nickel-based superalloys are extensively used in critical parts of modern aero engine and gas turbine. The hot deformation behaviors of a typical nickel-based superalloy are investigated by hot compression tests with strain rate of (0.001–1) s^{-1} and forming temperature of (920–1040) °C. Results show that the flow stress is sensitive to the forming temperature and strain rate. With the increase of forming temperature or the decrease of strain rate, the flow stress decreases significantly. Under the high forming temperature and low strain rate, the flow stress–strain curves show the obvious dynamic recrystallization. Based on the stress–dislocation relation and kinetics of dynamic recrystallization, a two-stage constitutive model is developed to predict the flow stress of the studied nickel-based superalloy. Comparisons between the predicted and measured flow stress indicate that the established physically-based constitutive model can accurately characterize the hot deformation behaviors for the studied nickel-based superalloy.

1. Introduction

Generally, material flow behaviors during hot forming processes (such as rolling, forging, and extrusion) are often complex [1]. It is well known 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 [2,3]. For the multi-pass hot forming process, the static and metadynamic recrystallizations [4–7] also occur. The hardening and softening mechanisms are both significantly affected by the thermo-mechanical parameters, such as forming temperature, deformation degree, and strain rate. On the one hand, a given combination of thermo-mechanical parameters determines the final microstructures and properties of the products. On the other hand, microstructural changes in alloys during the hot-forming in turn affect the flow behaviors, and hence influence the forming process. The constitutive relations are often used to describe the plastic flow properties of metals and alloys in a form that can be used in the computer code to simulate the thermo-mechanical response of mechanical parts under the prevailing loading conditions [1,8,9].

In recent years, many constitutive models have been developed or improved to describe the flow behaviors of metals or alloys. Lin and Chen [1] presented a critical review on some experimental results and constitutive descriptions for metals and alloys under hot working in recent years, and the constitutive models are divided into three categories, including the phenomenological [9–35], physically-based [36–38] and artificial neural network models [39–45], to introduce their developments, prediction capabilities, and application scopes. One of the most commonly-used phenomenological constitutive models is the Arrhenius hyperbolic-sine equation. Lin et al. [10] proposed a modified Arrhenius model to characterize the hot deformation behavior of 42CrMo steel by the compensation of strain and strain rate. Also, similar modified Arrhenius models were developed to predict the flow behaviors of 2124-T851 aluminum alloy [11], 800H superalloy [12], modified 9Cr–1Mo (P91) steel [13], Ni–20.0Cr–2.5Ti–1.5Nb–1.0Al superalloy [14], Inconel 600 superalloy [15], as-extruded 7075 aluminum alloy [16], TC4-DT alloy [17], Mg–Zn–Cu–Zr magnesium alloy [18], as-cast 21Cr economical duplex stainless steel [19], CP–Ti alloy [20], AISI 321 austenitic stainless steel [21], Al–3Cu–0.5Sc alloy [22], GCr15 steel [23], as-cast Ti60 titanium alloy [24], cast A356 aluminum alloy [25], and Ni–42.5Ti–7.5Cu alloy [26]. Considering the coupled effects of strain, strain rate and forming temperature on the material flow behaviors of Al–Zn–Mg–Cu and Al–Cu–Mg alloys, Lin et al. [27–30] proposed new phenomenological constitutive models to describe the thermo-viscoplastic responses of Al–Zn–Mg–Cu and Al–Cu–Mg alloys under hot working condition. In their proposed models, the material constants are presented as functions of strain rate, forming temperature and strain. Amongst the empirical and

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semi-empirical models, Johnson–Cook model [1] was successfully used to predict the hot deformation behaviors of a variety of materials. Also, some modified Johnson–Cook model were established to predict hot deformation behaviors of 42CrMo steel [31], boron steel sheet [32], titanium matrix composites [33], boron steel B1500HS [34], and 20CrMo alloy steel [35]. Based on the classical stress–dislocation relation and the kinetics of dynamic recrystallization, the constitutive equations were established to describe the flow stress during the working hardening-dynamic recovery and dynamical recrystallization periods for 42CrMo steel [36], 7050 aluminum alloy [37], and N08028 alloy [38]. In addition, neural network models were developed to predict the flow stresses of 42CrMo steel [39], A356 aluminum alloy [40], as-cast 904L austenitic [41], Al/Mg based nanocomposite [42], glass fiber reinforced polymers [43], as-cast Ti–6Al–2Zr–1Mo–1V alloy [44], and 28CrMnMoV steel [45].

Due to their comprehensive strength and toughness, excellent mechanical properties and high resistance to oxidation and corrosion, nickel-based superalloys are extensively used in critical parts of modern aero engine and gas turbine [46,47]. Generally, the nickel-based superalloy components are made through the complex thermo-mechanical processes, and their properties are significantly sensitive to the forming temperature, strain rate, as well as strain [48,49]. Therefore, in order to achieve the excellent properties of nickel-based superalloy parts, it is significant to investigate the hot deformation behaviors and optimize the thermo-mechanical processing parameters. Due to the limited forming temperature range and complex microstructural evolution, the hot deformation characteristics and microstructural evolution of the nickel-based superalloys were carried out by many researchers [46–53]. Ning et al. [46] investigated the hot deformation behavior of GH4169 superalloy associated with stick δ phase dissolution during the isothermal compression process, and found that the δ phase has great effects on the DRX and high-temperature flow behavior of GH4169 superalloy. Wang et al. [49] investigated the hot deformation of X-750 nickel-based superalloy, and established the processing maps for the studied material. Ning et al. [50] 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. Wang et al. [51,52] studied the hot deformation behaviors of superalloy 718 with δ phase, and confirmed that the nucleation mechanisms of DRX in superalloy 718 are strongly dependent on the Zener–Hollomon parameter. Wu et al. [53] studied the hot compressive deformation behavior of a new hot isostatically pressed Ni–Cr–Co based powder metallurgy superalloy. Obviously, previous studies [1] mainly developed or improved the phenomenal models to describe the flow behavior of nickel-based superalloys. Although these modes can give an accurate and precise estimate of the flow stress, the clear physical meanings are still absent. Therefore, the physically-based constitutive models for nickel-based superalloys should be further studied.

In this study, the hot deformation behaviors of a typical nickel-based superalloy are investigated by isothermal compression tests with the wide ranges of forming temperature and strain rate. Based on the experimental results, a physically-based model considering dynamic recovery and dynamic recrystallization mechanisms is developed to describe the relationship between the flow stress, strain rate, and forming temperature.

2. Materials and experiments

The chemical compositions (wt.%) of the studied nickel-based 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. All the specimens were solution treated at 1040 °C for 0.75 h, then followed by the water quenching. Fig. 1 shows the microstructure of the studied superalloy before the hot deformation. It is found that the microstructure is composed of fine equiaxed grains with a mean size of 75 μm. Hot compression tests were conducted on Gleeble-3500 thermo mechanical simulator under the forming temperatures of 920, 950, 980, 1010, and 1040 °C. The strain rates were selected as 0.001, 0.01, 0.1, and 1 s^{-1}, and the height reduction was 70%. Prior to the hot compression, all specimens were heated at a rate of 10 °C/s and soaked for 300 s at the forming temperature. Tantalum foil with the thickness of 0.1 mm was used between the specimen and dies to reduce the friction. The stress–strain data were automatically recorded by the testing system during the hot compression. In order to study the effects of the forming processing on the microstructure, the specimens were immediately quenched by water after hot compression. Then, the deformed specimens were sliced along the compression axis section for microstructure 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).

3. Results and discussion

3.1. Flow characteristics of the studied superalloy

Due to the unavoidable interfacial friction between the specimen and dies, the deformation is inhomogeneous, and the deformed specimens reveal the barrel-type shape [41]. Generally, the calculated flow stress–strain curves overestimate the actual ones. Therefore, the effect of friction on the flow stress should be considered to acquire the accurate true stress–strain curves of the studied superalloy. In present study, the detailed method to correct the flow stress can be found in Refs. [54,55]. Fig. 2 shows the true stress–strain curves considering the effects of friction on the hot deformation behavior of the studied superalloy. Obviously, the flow stress is significantly influenced by the forming temperature and strain rate. From Fig. 2a, it can be found that the flow stress increases with decreasing the forming temperature under given strain rate. This is because the number of slip systems is limited, and the process of softening is not obvious under relatively low forming temperatures. Therefore, the work hardening mechanisms, such as dislocation intersections and pileups, lead to the increasingly high stress for the continuous deformation. While the rates for the vacancy diffusion, cross-slip of screw dislocations

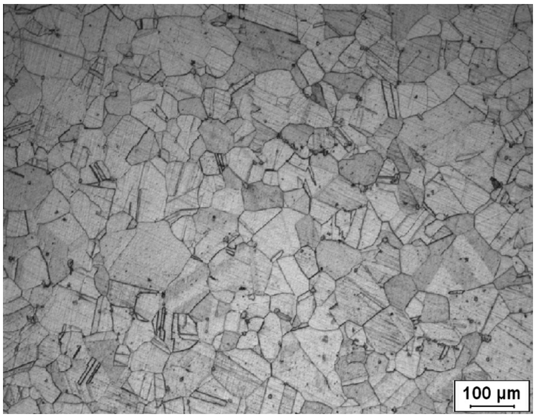

Fig. 1. Microstructure of the studied superalloy before the hot deformation.