Journal of Alloys and Compounds 741 (2018) 85–96

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Hot deformation behavior and constitutive modeling of fine grained Inconel 718 superalloy

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A R T I C L E I N F O

Article history:
Received 16 August 2017
Received in revised form
14 November 2017
Accepted 23 December 2017
Available online 28 December 2017

Keywords:
Inconel 718 superalloy
Hot deformation
Microstructure
Dynamic recrystallization
Processing map

A B S T R A C T

The hot deformation behavior of fine grained Inconel 718 superalloy was investigated by compression test in the temperature range of 950 to 1150 °C and strain rate range of 0.1–10 s^{-1}. At low temperatures and high strain rates, the flow stress rapidly increased to a peak value with increasing strain at the initial stage of deformation. After attaining peak stress, the flow curves exhibited an obvious phenomenon of flow softening. At high temperatures and low strain rates, the flow curves exhibited typical characteristics of dynamic recrystallization. A strain-compensated Arrhenius type constitutive equation was used to predict the flow behavior of the alloy. The relationship between the material constants (i.e. α, Q, n and $\ln A$) in Arrhenius-type constitutive equation and true strain was established by a fifth order polynomial. The flow stress values predicted by the developed constitutive equations were in good agreement with the experimental values, showing that the developed constitutive equation can give a precise estimate for the flow stress during hot deformation. The processing maps of fine grained Inconel 718 superalloy for hot working at different strains were constructed. The optimum processing parameters were determined to be the deformation temperature of 1100 °C and strain rate of 0.1 s^{-1}.

1. Introduction

Inconel 718 superalloy is a typical nickel-base superalloy strengthened predominately by coherently ordered gamma double prime (γ''-Ni_3Nb) precipitates [1–4]. Inconel 718 superalloy is used widely for critical parts of gas turbines, rocket engines and power generators, and other high temperature load bearing components because of their unusual ability to retain excellent combinations of mechanical properties and corrosion resistance at higher temperatures up to 650 °C [5–7]. Inconel 718 superalloy is one of the most difficult-to-deformation material due to its great deformation resistance and narrow hot-working temperature range. Hot deformation in actual industrial processes such as hot rolling, hot forging and hot extrusion has been widely used for manufacturing of both semi-finished and finished products of Inconel 718 superalloy. The mechanical properties of the critical parts are dependent on the microstructure developed during manufacturing processes of Inconel 718 superalloy. Therefore, Better control of the thermomechanical processing is of great importance for Inconel 718 superalloy to obtain a superior performance.

It is well known that the hot deformation behavior of nickel-based superalloy is affected significantly by initial grain size, morphology of secondary phase and processing parameters such as deformation temperature, strain rate and deformation degree [8–14]. Therefore, it is of great importance to investigate the hot deformation behavior of Inconel 718 superalloy and optimize the parameters to improve its moldability. In recent years, many researches on the hot deformation behavior of Inconel 718 superalloy have been launched under different deformation conditions [9–18]. Yuan and Liu [9] reported the effect of the δ phase on the hot deformation behavior of Inconel 718. The results showed that the δ phase increased the apparent activation energy of deformation, decreased the peak strain and the peak stress, and promoted the flow softening after the peak stress. Thomas et al. [10] and Wang et al. [12,13] also found that the existence of higher fraction of undissolved δ phases have an obvious influence on the apparent activation energy of deformation and the nucleation mechanism of dynamic recrystallization of Inconel 718 superalloy. Sui et al. [14] investigated the processing map for hot working of Inconel 718 superalloy at the temperature range of 950–1150 °C and strain rate

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https://doi.org/10.1016/j.jallcom.2017.12.265
0925-8388/

range of 0.001–100 s^{-1}. The results showed that the distribution of dynamic recrystallization zone in stable region is from lower temperature and lower strain rate to higher ones, and a peak efficiency of 0.39 occurs at about 950 °C and 0.001 s^{-1}. Wang et al. [15] and Lin et al. [17] developed a new constitutive model for high-temperature deformation behavior of Inconel 718 superalloy. The relationship between deformation temperature, strain rate and flow stress during hot deformation of the Inconel 718 superalloy was described by a new constitutive model. It is noted that these researches are mainly focused on the flow behaviors, dynamic recrystallization and processing maps of the Inconel 718 superalloy with coarse grain size. The initial grain size also exhibited a significant effect on the microstructural characterization, recrystallization behavior and optimum final-forging parameter of the materials during hot deformation [8,14,19,20]. The alloy with coarse initial grain size could result in a larger recrystallized grain size and higher flow stress during hot deformation, while the alloy with fine initial grain size could decrease the flow tress and recrystallized grain size. Also, the optimum hot-working parameters was obtained at lower deformation temperature and higher strain rate for the alloy with fine initial grain size [19,20]. In order to obtain fine recrystallized grain size and improve the mechanical properties of Inconel 718 superalloy, it is necessary to study the hot deformation behavior of fine grained Inconel 718 superalloy. However, few investigations were reported about the hot deformation behavior of fine grained Inconel 718 superalloy (≤10 μm). In order to understand the hot deformation behavior of fine grained Inconel 718 superalloy, in this present work the Inconel 718 superalloy was solution-treated at 980 °C for 90 min to produce the samples with fine grain structure. Hot compression tests were conducted in the temperature range of 950 to 1150 °C and strain rate range of 0.1–10 s^{-1}. The processing maps for hot working at different strains were constructed to optimize the processing parameters.

2. Experimental

2.1. Material and sample preparation

The chemical compositions (wt.%) of Inconel 718 superalloy used in this investigation was listed in Table 1. The as-received alloy was a wrought billet with a diameter of 252 mm. To investigate the hot deformation behavior of fine grained Inconel 718 superalloy, the alloy was solution-treated at 980 °C for 90 min in a muffle furnace followed by water quenching. The initial microstructure of the heat-treated alloy is given in Fig. 1. It is seen that the initial microstructure of the alloy consisted of fine equiaxed grains. The average grain size was measured to be about 10 μm by using the Image-Pro Plus 6.0 software.

2.2. Hot compression test

Cylindrical compression specimens of 12 mm in height and 8 mm in diameter were machined from the heat-treated bars. Hot compression tests were conducted on the Gleeble 3800 thermo-mechanical simulator in the deformation temperature range of 950 to 1150 °C and strain rate range of 0.1–10 s^{-1}. The specimens were heated by the direct resistance heating system. The temperature was controlled with a NiCr-NiSi thermocouple spot welded at the mid-span of the specimen. The graphite lubricant was coated on the top and bottom surfaces of specimen, and the tantalum foil with the thickness of 0.1 mm was placed between the cylindrical specimen and the tool to assist in reducing friction and avoid the adhesion. Hot compression tests were carried out in an argon atmosphere. Specimens were heated to the deformation temperature at a rate of 10 °C/s and soaked for 2 min to eliminate the thermal gradient prior to deformation. The specimens were deformed to a true strain of 1.2 at the deformation temperatures of 950 to 1150 °C and strain rates of 0.1–10 s^{-1}. The stress-strain data were automatically recorded by testing system during the hot deformation. Immediately after deformation, the specimens were rapidly quenched with water sprays to room temperature so as to preserve the deformed microstructure. The deformed specimens were sectioned parallel to the compression axis through the center to observe the microstructural evolution. Specimens for optical microscopy were mechanically polished and etched electrolytically with a solution of 13 pct hydrofluoric acid (HF), 7 pct nitric acid (HNO_3), and 80 pct hydrochloric acid (HCl). Microstructure examination was performed on a Leica DMI5000M optical microscope (OM). Specimens for electron backscatter diffraction (EBSD) examination were ground, mechanically polished, and then electro-polished in an electro-polishing solution of 200 ml ethanol and 10 ml perchloric acid at a voltage of 20 V for 30 s. EBSD measurements were carried out on SUPRA40 SEM at 20 keV. The step size for EBSD orientation mapping was 0.4 μm.

Table 1
Chemical composition of the Inconel 718 superalloy (Wt. %).

Ni	C	Si	Mn	S	P	Cr	Mo	Al	Ti	Nb	B	Fe
52.3	0.08	0.45	0.5	0.01	0.01	18.6	3	1.2	0.8	4.9	0.004	Bal

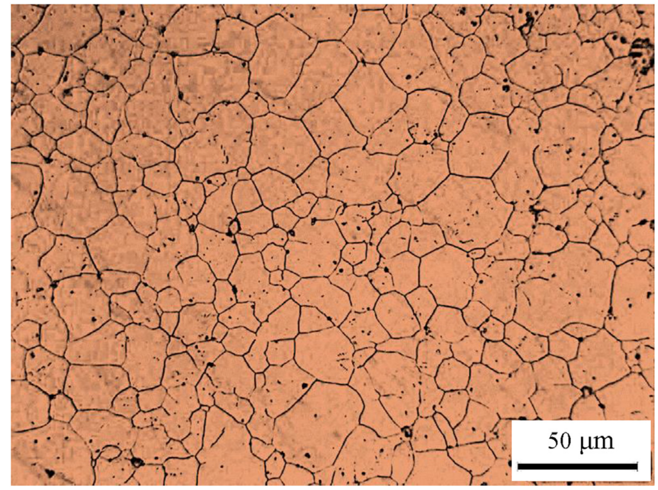

Fig. 1. Microstructure of the Inconel 718 superalloy after the heat treatment at 980 °C for 90 min.

3. Results and discussion

3.1. True stress-strain curves

The true stress-strain curves were measured to help in identifying the mechanism of hot deformation. Fig. 2 shows the true stress-strain curves of fine grained Inconel 718 superalloy at various deformation temperatures of 950 to 1150 °C and strain rates of 0.1–10 s^{-1}. It is seen that the true stress-strain curves exhibited completely different shapes depending on the deformation temperature and strain rate. When the strain was small, the work hardening effect played a dominant role, so the flow stress increased very fast at this moment, and rapidly increased to a peak value with increasing strain. Both the peak stress and the peak strain were found to decrease with increasing deformation temperature and decreasing strain rate. After attaining peak stress, the