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Plastic deformation and dynamic recrystallization of a powder metallurgical nickel-based superalloy

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ABSTRACT

The mechanisms of hot plastic deformation and dynamic recrystallization (DRX) in a powder metallurgical superalloy were investigated by compression tests in the deformation temperature range of 1020–1140 °C, and the constant strain rate range of 0.001–1.0s^{-1}. The results showed that the stress–strain curves can indicate the intrinsic relationship between the flow stress and thermo-mechanical behavior, which can be used to reflect the internal micro-structural evolution law. All of curves can be divided into three types of DRX flow curves: single peak, cyclic behavior and steady-state flow stress curve. Based on researching of basic constitutive relation, the peak stress can be expressed as follows:$\sigma_p = 0.00013Z^{0.177}$. The mechanisms of DRX depended on the operating deformation mechanisms which changed with temperature and strain rate. The inflection point of work-hardening rate curve indicates the onset of DRX. The inflection points are obvious at a low strain rate and a high temperature, while they are not existence at a high strain rate and a low temperature. The strain-rate sensitivity, and thus the deformation mechanisms, are different in the respective temperature regimes as found for the steady-state flow stress and the peak stress, and reflected by the temperature dependence of the stress exponent. Continuous dynamic recrystallization (CDRX) takes place at low deformation temperature. CDRX can lead to a partial softening in hot deformation. A great number of the dislocations are trapped by subgrain boundaries, leading to an increase in grain boundary misorientation and gradual transformation into high-angle grain boundaries (HABs). Discontinuous dynamic recrystallization (DDRX) takes place at high deformation temperature. A great number of new grains formed on the completely dynamic recrystallization microstructure.

1. Introduction

Superalloys are widely used to fabricate jet engine components because of their good microstructure stability, excellent mechanical properties, good ultimate strength and creep performance at elevated temperature [1–5]. With the development of modern aviation industry, higher performance requirements are essentially necessary for high temperature structural components. As a result, powder metallurgy (PM) superalloy has been developed rapidly for its excellent performance, which is a new type of superalloy with high alloy content and without alloy segregation. Because of the high alloying content in this type of superalloy, the high temperature deformation becomes a key problem [6]. Therefore, it is very important to investigate the plastic deformation behavior at high temperature.

Because of the high alloying content and the special production technique for this type of PM superalloy, the deformation behaviors of this superalloy are different from that of the traditional superalloy. Several recent papers have reviewed the hot deformation behaviors of the PM superalloy, however, there are few references can be found about the different processes for microstructure evolution. This article makes a deep study on the different processes for microstructure evolution in the process of hot deformation.

As an important working technique, hot plastic deformation is broadly applied in industry field especially in aerospace manufacturing industry. In this paper, the process of forging was simulated by means of the hot compression tests. Hot plastic deformation as a complex process includes dislocation multiplication, work hardening behavior, dynamic recovery, dynamic recrystallization, constitutive model and microstructure evolution

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[7–10]. All of them are affected by deformation temperature, strain rate and true strain.

In this work, the hot plastic deformation behavior of powder metallurgy superalloy FGH4096 has been investigated based on the isothermal compression tests conducted at different deformation parameters. The work hardening behavior, dynamic recovery, dynamic recrystallization, constitutive model and microstructure evolution in the hot plastic deformation has been analyzed to understand the hot deformation mechanisms.

It highlights the microstructure development issue, that is, aiming at knowing what hot deformation conditions have to be controlled in such a way as to promote a specific mechanism that leads to a desired microstructure, and delivering an excellent high temperature property.

2. Experimental materials and experimental details

The powder metallurgy superalloy FGH4096 was fabricated by means of metal powder sintering using nickel-base superalloy powders. The prealloyed powder particles with a diameter ranging from 50 to 150 μm were prepared by plasma rotating electrode process. The powder was encapsulated in a stainless steel capsule and the HIPed billet was fabricated by duplex HIP under the condition of 1030°C/120 MPa/1 h + 1170°C/140 MPa/2 h. The nominal chemical composition (wt.%) of the as-HIPed FGH4096 superalloy used in this investigation is listed in Table 1.

The cylindrical compression specimens 12 mm in length and 8 mm in diameter were machined from the post forged bar. It is necessary to ensure that the end surfaces are perpendicular to the sample axis. Besides, the end faces of the specimens should be grinded on the grinding machine in order to reduce the surface roughness. Isothermal hot compression tests were carried out on a Gleeble-1500D thermo-simulation machine in the deformation temperature range of 1020–1140 °C, and the constant strain rate range of 0.001–1.0s^{-1}. All the specimens were heated at a heating rate of 10 °C/s and soaked for 5 min at the testing temperature in order to obtain a uniform microstructure in the entire specimen before hot compression test. The testing temperatures were controlled to ±2 °C. The specimens were compressed to 50% of the original height followed by quenching with a water jet immediately after the hot deformation was stopped. In the process of compression tests, the load-stroke curves were automatically converted into true stress-true strain curves using standard equations. After hot deformation, the deformed specimens were cut along the compression axis for microstructure observation. In order to analyze the effects of the forming processing parameters on the microstructures, the grain structures of the deformed specimens were observed by an Olympus PM3 optical microscope (OM).

3. Results and discussion

3.1. Analysis of DRX flow stress behavior

The true stress-true strain curves at different deformation temperatures and strain rates are shown in Fig. 1. These stress–strain curves not only can be used to shown the relationship between flow stress and deformation temperature and strain rate, but also can be indicative of the relationship between work hardening and dynamic softening. As shown in Fig. 2, all of the stress–strain curves can be divided into three types of DRX flow curves: single peak (1020 °C–1 s^{-1}), cyclic behavior (1110 °C–1 s^{-1}), and steady flow stress curve (1140 °C–0.001 s^{-1}).

The true stress-true strain curves at low deformation temperature and high strain rate can be characterized as single peak behavior. In this type, the stress–strain curves show an obvious softening phenomenon. The flow stress increases rapidly as the true strain increased until a peak stress at a very small strain. Moreover, the peak stresses decrease with an increase in the forming temperature or a decrease in strain rate. In the following deformation period, the flow stress decreases markedly with the increase of true strain. Conversely, the true stress-true strain curves at high deformation temperature and high strain rate can be characterized as cyclic behaviors. In this type, the stress–strain curves take on characteristic of multi peak stress. The flow stress increases rapidly as the true strain increased, and a multiple peak (cyclic) behavior can be noticed, in which the repetition of stress fluctuations is observed before the continuous falling of flow stress. This phenomenon may be attributed to the occurrence of several independent cycles of DRX. Furthermore, there are signs of another type of DRX flow curves at high deformation temperature and low strain rate, which can be considered as a steady flow stress curve. In this type, the flow stress increases rapidly as the true strain increased, then the flow stress remains a constant during steady state deformation. There is not an obvious peak stress in this type of flow stress curve.

3.2. Work hardening behavior (θ–σ)

The shape of flow stress curve depends on work hardening rate ($\theta = d\sigma/d\varepsilon$). As the Fig. 2 shown, three different work-hardening features have been demonstrated in different typical shapes of flow curves: shape I ($\theta > 0$ for work hardening stage), shape II ($\theta = 0$ for steady stage) and shape III ($\theta < 0$ for continuous softening stage) [11]. Owing to the same expression with external power dissipation efficiency in non-equilibrium thermodynamics [12], work hardening rate $\theta = d\sigma/d\varepsilon$ has been widely employed to investigate the transformation of microstructure during hot deformation [13]. The stress peak is not identical with the onset of DRX, rather reduction of DRX has to occur before ε_p is reached. From the principles of irreversible thermodynamics, Poliak–Jonas [14] criterion has been utilized to identify the onset of DRX with the point on the work hardening curve where, at maximum energy storage, the dissipation rate is at a minimum. The critical stresses for occurrence of DRX (σ_c) by the inflection points in the work hardening rate θ versus flow stress σ curves or the minimums in $-(\partial\theta/\partial\sigma)$ curves.

In the process of hot deformation, the critical stresses for initiation of DRX appeared before the stress peak. So the most attention should be paid to the competition mechanism between work-hardening with dynamic softening during the work hardening stage before peak stress. In order to obtain the values of work hardening rate during work hardening stage, the following incremental equation was used:

$$\theta|_i = \frac{d\sigma}{d\varepsilon}\bigg|_i = \frac{\sigma|_{i+1} - \sigma|_{i-1}}{\varepsilon|_{i+1} - \varepsilon|_{i-1}} \tag{1}$$

From Eq. (1) it can be seen that the values of work hardening rate at different strain can be obtained based on the flow stress and strain. In the present study, the relationship between work hardening rate and true strain can be obtained base of Eq. (1) in combination with the measured results of the flow stress curves in

Table 1
Chemical composition of powder metallurgical superalloy FGH4096 (mass fraction, %).

C	Cr	Co	W	Al	Ti	Fe	Mo	Ni
0.03	16.05	12.72	4.04	2.20	3.70	0.25	3.53	Bal