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Hot deformation behavior of GH4945 superalloy using constitutive equation and processing map

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ABSTRACT

The hot deformation behavior of GH4945 superalloy was investigated by isothermal compression test in the temperature range of 1000－1200 ℃ with strain rates of 0.001－10.000 s^{-1} to a total strain of 0.7. Dynamic recrystallization is the primary softening mechanism for GH4945 superalloy during hot deformation. The constitutive equation is established, and the calculated apparent activation energy is 458.446 kJ/mol. The processing maps at true strains of 0.2, 0.4 and 0.6 are generally similar, demonstrating that strain has little influence on processing map. The power dissipation efficiency and instability factors are remarkably influenced by deformation temperature and strain rate. The optimal hot working conditions are determined in temperature range of 1082－1131 ℃ with strain rates of 0.004－0.018 s^{-1}. Another domain of 1134－1150 ℃ and 0.018－0.213 s^{-1} can also be selected as the optimal hot working conditions. The initial grains are replaced by dynamically recrystallized ones in optimal domains. The unsafe domains locate in the zone with strain rates above 0.274 s^{-1}, mainly characterized by uneven microstructure. Hot working is not recommended in the unsafe domains.

1. Introduction

Nickel-based superalloy GH4945 possesses perfect matching of high strength and outstanding corrosion resistance, which makes it broadly applied in very harsh service environment, such as oil and gas industry. The structural components used in these conditions are subjected to the combined attacks from high temperature, high stress and corrosive medium[1,2]. Superalloy usually gains desired microstructure and necessary product performance for special use by hot working (forging/rolling) and following heat treatment. Recent researches about GH4945 superalloy mainly concerned its mechanical properties[3]. Generally, the performance strongly depends on the microstructure, which is significantly affected by hot working conditions. Nevertheless, the research on processing technology for GH4945 superalloy was involved little, particularly the one to obtain a homogeneous and fine microstructure in a hot-deformed product had not been fully established. It is necessary to acquire a proof about the effects of processing parameters, such as temperature, strain rate and strain, on microstructural evolution during hot deformation. In order to obtain GH4945 superalloys with desired microstructure, there is an urgent need to get a comprehensive understanding of hot deformation characteristics.

As is known to all, the flow stress is often used to investigate plastic deformation features of alloys and metals, determining the load and energy required during deformation[4]. It has been commonly believed that the constitutive equation is a very efficient way to depict the plastic flow behavior of metal materials for numerical simulations (i. e., prediction of flow stress during hot working), which has acquired great achievements when applied to various metal materials such as nickel-based superalloy[5], stainless steel[6], aluminum alloy[7] and magnesium alloy[8]. In the last few years, the processing map, a significant model originated from dynamic materials

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model (DMM), has been applied extensively in optimizing workability of alloy and controlling deformation microstructure[9,10]. On the basis of processing maps, the deformation behavior under various conditions during hot working can be analyzed. Usually, the optimal hot working parameters refer to deformation temperature and strain rate corresponding to regional peak value of power dissipation efficiency[11,12].

In the present study, the hot deformation behavior of GH4945 superalloy was studied over wide and practicable temperatures and strain ranges by isothermal compression tests. The constitutive equation based on experimental results was established and examined. The processing maps were established, which provided a basis for the hot working parameters optimization. The microstructures of the deformed specimens were observed to verify the processing maps.

2. Experimental Procedures

GH4945 superalloy produced by vacuum induction melting was used for this study, and its chemical composition is listed in Table 1. Compression samples of 8 mm in diameter and 12 mm in height were prepared from a forged bar with diameter of 16 mm. The isothermal compression tests were conducted using a Gleeble-1500 thermal-mechanical simulation testing machine at the temperatures of 1000, 1050, 1100, 1150 and 1200 ℃ with the strain rates of 0.001, 0.01, 0.1, 1 and 10 s^{-1}. In order to get uniform microstructure, all samples were heated to 1200 ℃ at a rate of 20 ℃/s prior to testing, then cooled down to the specified deformation temperature at a rate of 10 ℃/s and held for 30 s at the temperature to obtain homogenous distribution of deformation temperature. All samples were subjected to 50% height reduction corresponding to true strain of 0.7. To preserve the deformed microstructure, the samples after hot deformation were promptly quenched by water.

Table 1
Chemical composition of GH4945 superalloy (wt. %)

C	Cr	Mo	Cu	Al	Ti	Nb	Fe	Ni
0.016	20.23	3.39	2.01	0.24	1.54	3.02	20.93	Balance

The metallographic samples were cut parallel to the compression axis, and the microstructural observation was carried out on an optical microscope (OM, OLYMPUS GX71). The sample preparation process includes: mechanical grinding, polishing and then boiling in a solution of 2.5 g potassium permanganate, 10 mL concentrated sulfuric acid and 90 mL water.

As shown in Fig. 1(a), the initial microstructure of GH4945 superalloy after hot forging mainly consists of equiaxed recrystallized grains with mean grain size of about 65 μm. GH4945 superalloy has precipitates of Ni_3(Ti, Nb, Al)-type γ' phase and Ni_3(Nb, Ti, Al)-type γ'' phase with sub-micron size embedded in a disordered FCC γ matrix (Fig. 1(b)).

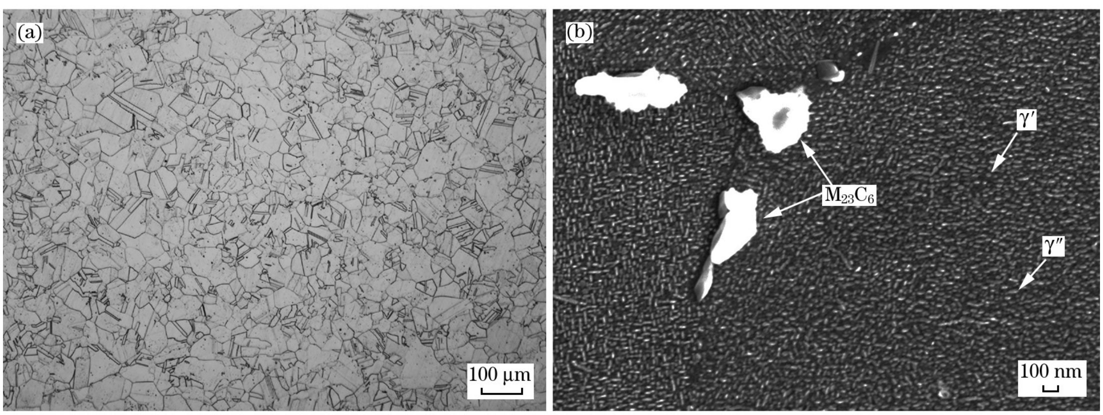

Fig. 1. Initial optical microstructure of GH4945 superalloy after hot forging (a) and morphology of precipitates (b).

3. Results and Discussion

3.1. True stress-strain curves

Fig. 2 illustrates the true stress-true strain curves of GH4945 superalloy compressed at various temperatures and strain rates. Similar characteristics can be observed among the flow stress curves: flow stress decreases with the increase of temperature and decrease of strain rate. A single peak can be observed when the strain gets to a critical value. After that, the so-called "strain-softening stage" appears in the curve. Hence, the flow stress comes to a steady state under the condition of high strain. The work hardening results in the increase of stress in the early stage, which is a consequence of poorly developed subgrain boundaries and the increased dislocation density[13].