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Plastic deformation behavior and processing maps of a Ni-based superalloy

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ABSTRACT

Hot compression tests of a kind of Ni-based superalloy were performed under the conditions of temperatures of 1223 K, 1273 K, 1323 K, 1373 K, 1423 K, the strain rates of 0.001 s^{-1}, 0.1 s^{-1}, 1 s^{-1}, 3 s^{-1}, 30 s^{-1}. Processing maps were established on the basis of the data achieved from the hot compression tests by using the principle of dynamic materials modeling. The microstructure evolution and the dislocation of the samples after tests were observed. Through the analysis of the processing maps, it can be known that the samples in the process of the deformation can achieve the peak efficiency of about 35% when the temperature is above 1273 K, strain rate locates in 0.1–2 s^{-1}. The result of metallographic analysis shows that the proportion of dynamic recrystallization in the peak efficiency domain is higher than that in other domains. It can be found that the dislocation density is very high in the low efficiency or instability domain where dynamic recrystallization does not occur or the proportion of dynamic recrystallization is low. The optimum deformation condition of the Ni-based superalloy can also be found through the analysis of processing maps.

1. Introduction

Ni-based superalloy is a kind of material that develops very fast under the development of aerospace and navigation. It is widely used in aviation engine turbine and other important loaded parts. Ni-based superalloy can work under extremely harsh conditions for a long time. It has perfect high temperature performance, which can be served above 973 K for a long time and also has good comprehensive performance within the scope of 773–1073 K. It is particularly important to understand the deformation behavior of Ni-based superalloy under high temperature because hot forming methods are usually used in the processing of this material [1–3]. And it is a good choice to establish the processing maps through the true stress–strain curves of the material achieved by the hot compression tests [4–5,8–14], the established processing maps can help to find the optimal hot deformation parameters.

Extensive researches have been conducted about the hot deformation behavior and processing maps of superalloys, and most of them are try to establish processing maps through experiments and then directly figure out the peak efficiency domains [1–6]. Wu and Liu [7] studied hot compressive deformation behavior of a new hot isostatically pressed Ni–Cr–Co based powder metallurgy superalloy, the result shows that the processing maps of this alloy have several peak efficiency domains. Fang et al. [8] investigated the constitutive relationships and processing maps for FGH96 alloy during two-pass hot deformation and two instability zones of flow behavior were respectively established as follows: $T = 1353$–1398 K, $\dot{\varepsilon} = 0.01$–0.1 s^{-1}, $\varepsilon < 0.2$ and $T = 1323$–1398 K, $\dot{\varepsilon} = 0.01$ s^{-1}, $\varepsilon > 1$, which should be avoided during hot deformation. Liu et al. [9] investigated the effect of true strains on processing map for isothermal compression of Ni–20.0Cr–2.5Ti–1.5Nb–1.0Al Ni-base superalloy, the result shows that the hot deformation can be carried out firstly at 1253 K and 0.001 s^{-1} with small strain about 0.35 and then carried out at 1293 K and 1.0 s^{-1} to get fine homogeneous microstructure. Wang et al. [10] established processing maps of X-750 nickel-based superalloy and found that the optimum parameters for hot working of this alloy are deformation temperature of 1273–1323 K and strain rate of 0.1–1 s^{-1}. Cai et al. [12] revealed the characterization of hot deformation behavior of a Ni-base superalloy by using processing map and found that a domain of dynamic recrystallization (DRX) exists in the temperature range of 1373–1423 K and strain rate range of 0.001–0.01 s^{-1}, with its peak efficiency of 56% and about 1398 K and 0.001 s^{-1}, which are the optimum hot working parameters. The investigations by others [15–21] show that the processing maps include efficiency and instability maps, and both of them

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can established by the data obtained from the hot expression tests, so the accuracy of the data is very important. The most suitable domains for hot deformation can obtained from the analysis of the processing maps if the data obtained from the tests are reliable.

In this study, plastic deformation behaviors of a Ni-based superalloy were investigated by isothermal compression tests under the wide ranges of forming temperatures and strain rates. The effects of forming temperature, strain rate and strain on the flow behaviors of the Ni-based superalloy were discussed. The processing maps of this alloy were established to find out which conditions are most likely to instability and to optimize the hot working domains. In addition, evolution of the microstructures under different conditions were analyzed to verify the established processing maps of the Ni-based superalloy.

2. Materials and experimental details

The chemical compositions (wt%) of the Ni-based superalloy used in the hot compression tests are as follows: Ni 75.60, Cr 14.52, Mo 3.18, Ti 2.68, Nb 2.02, Al 1.71, C 0.042, Fe <0.21. The corrosion resistant capability of the Ni-based superalloy is very strong due to large amount of nickel in this alloy [7].

The hot compression tests were performed by using a MTS810.13 testing machine under constant strain rate and temperature each time. The size of each cylindrical sample is Ø10 mm × 16 mm. Deformation conditions such as temperature and displacement velocity were automatically controlled by computer system. The relevant data such as true stress and strain were also automatically recorded. In order to minimize the influence of the friction between chuck and workpiece, a certain thickness of about 1 mm of glass lubricant was smudged on cylindrical samples before compression. The parameters of hot compression tests are as follows: temperature as 1223 K, 1273 K, 1323 K, 1373 K, 1423 K, strain rate as 0.001 s^{-1}, 0.1 s^{-1}, 1 s^{-1}, 3 s^{-1}, 30 s^{-1} respectively. In order to analyze the effects of the forming processing parameters on the microstructures, the grain sizes of the deformed samples were observed by optical microscope. At the same time, the dislocation density of the samples was also observed by transmission electron microscope. The surfaces of the samples were ground and polished then etched before observation.

3. Results and discussion

3.1. True stress–strain curves

The true stress–strain curves obtained from hot compression tests are shown in Fig. 1. The characteristics of the true stress–strain curves are similar in all deformation conditions. This is because the deformation tests are all under high temperature, recovery and recrystallization will occur with the increase of strain under this condition. When the strain is small, the work hardening effect plays a dominant rule, so the flow stress increases very fast at this moment. With the increase of strain, the softening effect caused by recovery and recrystallization gradually turns to a dominant rule so the work hardening effect is reduced, the flow stress reaches the maximum value. After that softening effect and work hardening effect eventually turn to a dynamic balance, the platform of flow stress occurs. This is the reason why the characteristics of the true stress–strain curves are similar in all deformation conditions in the article.

Fig. 1 shows that the flow stress of the Ni-based superalloy increases gradually with the increase of strain rate under the condition of same temperature and strain. Flow stress increases rapidly with the increase of strain when the strain is very small, followed reaching maximum value, and then the flow stress trend towards stability. In addition, the flow stress reduces with the increase of temperature under the condition of the same strain and strain rate. The peak stress can be up to 780 MPa when the temperature is 1223 K and strain rate is 30 s^{-1}. However, the peak stress is 290 MPa when the temperature is 1423 K and strain rate is 30 s^{-1}. The former is 2.5 times of the latter.

3.2. Theory of processing maps

Forging temperature T and deformation rate $\dot{\varepsilon}$ are two of the most important parameters that can affect structure and property after forging. So how to choose the parameters is one of the major problems in the actual forging process. Processing maps of the alloy which are based on the true stress–strain curves can provide the basis for the parameter selection in the process of forging. It has been widely accepted that material thermal deformation model mainly includes atomic theory modeling, dynamic modeling and dynamic materials modeling. Dynamic materials modeling makes up the deficiency of the former two models and has been widely used in practice. The processing maps are established on the basis of dynamic material modeling.

According to the dynamic materials modeling, the total energy absorbed by the deformation object in the process of hot deformation dissipates mainly through the following two aspects: consumption in plastic deformation and structural transformation [22]. So the total energy absorbed by the object can be determined as

$$P = \sigma\dot{\varepsilon} = G + J = \int_0^{\dot{\varepsilon}} \sigma d\dot{\varepsilon} + \int_0^{\sigma} \dot{\varepsilon} d\sigma \tag{1}$$

where G refers to the power consumed in plastic deformation, J refers to the power consumed in structural transformation, and P refers to the total power absorbed by the object. The flow stress and strain rate sensitivity m can be expressed as follows:

$$\sigma = K(\dot{\varepsilon})^m \quad m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}} = \frac{\partial \lg \sigma}{\partial \lg \dot{\varepsilon}} \tag{2}$$

So the ratio between G and J can be determined by the strain rate sensitivity m as

$$\Delta J/\Delta G \approx m \quad \Delta J/\Delta P \approx m/(m+1) \tag{3}$$

In order to determine the proportion of the energy consumed in structural transformation, the parameter η can be used to describe the efficiency of power dissipation. It can be determined as

$$\eta = \frac{\Delta J/\Delta P}{(\Delta J/\Delta P)_{line}} = \frac{m/(m+1)}{1/2} = \frac{2m}{m+1} \tag{4}$$

where η is determined by $\varepsilon,\ \dot{\varepsilon},\ T$. When strain is a constant, η can be determined by strain rate and temperature. In the processing efficiency maps, larger value indicates that the proportion of the energy consumed in structural transformation is larger and the proportion of the dynamic recrystallization is also larger, which indicates the processing property is better.

However, the value of processing efficiency may be also high when the processing condition is in instability domain, the forms of instability include break, fold and so on. At this time, simply relying on processing efficiency maps cannot really reflect the processing property, so processing instability maps is necessary. Prasad criterion [23] can be expressed as follows:

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln\left(\frac{m}{m+1}\right)}{\partial \ln \dot{\varepsilon}} + m < 0 \tag{5}$$

where $m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}} = \frac{\partial \lg \sigma}{\partial \lg \dot{\varepsilon}}$, cubic spline function is adopted to fit the curves between $\lg \sigma$ and $\lg \dot{\varepsilon}$. So the relationship between strain rate sensitivity m under a certain temperature and strain can be described as $m = A + B \lg \dot{\varepsilon} + C \lg \dot{\varepsilon}^2$. Thus the Prasad criterion can be expressed as