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Hot working characteristic of as-cast and homogenized Ni–Cr–W superalloy

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ABSTRACT

The hot working behavior of as-cast Ni–Cr–W superalloy has been studied using constant strain rate isothermal compression tests in the temperature range 1000–1200 °C and strain rate range 0.001–10 s^{-1}. At lower strain rates ($\leq$0.1 s^{-1}), the flow curves exhibited a peak stress characteristic followed by a steady-state flow stress at large strains while continuous flow softening occurred at higher strain rates. The stress exponent value of 5.56 and apparent activation energy of 456 kJ/mol was calculated by a standard kinetic equation over the entire range of temperatures and strain rates. The power dissipation map exhibited a single domain in the temperature range 1050–1200 °C and strain rate range 0.01–0.001 s^{-1} with a peak efficiency of about 44% occurring at 1200 °C and 0.001 s^{-1}. Microstructural observations revealed that this domain represented dynamic recrystallization (DRX) and must be the optimum conditions for hot working the material. As predicted by continuum criterion, flow instabilities occurred in the form of adiabatic shear bands when deformed at strain rates above 0.1 s^{-1} and at temperatures below 1000 °C, and intercrystalline cracking occurred when deformed at 1200 °C and 10 s^{-1}.

1. Introduction

Ni–Cr–W superalloy is a relatively new system which is being explored in quest for excellent high temperature mechanical strength and long-term creep rupture strength when used at about 1000 °C [1]. In this alloy, both chromium and tungsten as solid solution strengthening elements decrease stacking fault energy of the alloy and lower diffusion coefficient of the alloy so that high temperature strength of the alloy is improved. Moreover, a small amount of carbon added in the alloy is used in forming carbides which prevent excessive grain coarsening and strengthen the grain boundary. As we all know, the prediction and control of microstructural change during the thermomechanical processing of metallic materials plays an important role with regard to optimizing subsequent service properties.

In recent years, processing maps have been successfully used for evaluating and optimizing the intrinsic workability of material and for controlling the microstructure of material to obtain the best combination of properties. The intrinsic workability is decided by the microstructural evolution under different temperatures, strain rates, and strains during the hot deformation process. This method is a very useful tool for optimizing the hot workability of a wide range of materials which also contain a number of commercial nickel-based superalloys [2–5]. Therefore, it was the objective of the present investigation to explore the hot deformation behavior of cast and homogenized Ni–Cr–W superalloy and to evaluate hot deformation mechanisms with a view to develop its potential as a wrought nickel-based superalloy. The hot deformation behavior is studied using several methods which include analysis of the shapes of flow curves, evaluating kinetic parameters and developing processing maps. In the present study, the above approaches will be applied for characterizing the hot deformation mechanisms of as-cast Ni–Cr–W superalloy, particularly focus on the processing maps.

The processing maps are developed on the basis of dynamic materials model (DMM) [6], the basis and principles of which are described in some earlier and recent literature [6,7]. In this model, the work-piece undergoing hot deformation can be considered as a dissipater of power and the efficiency of power dissipation (η) through microstructural changes is expressed by

$$\eta = \frac{2m}{m+1} \tag{1}$$

where m is strain rate sensitivity of flow stress. The variation of η with temperature and strain rate constitutes the power dissipation map which is usually viewed as a contour map representing iso-efficiency contours in a temperature and strain rate frame. The different domains in the power dissipation map may be correlated with specific microstructural mechanisms. The safe hot deformation mechanisms are dynamic recrystallization (DRX), dynamic recovery and superplasticity while wedge cracking and void formation at hard particles are damage processes.

The flow instability condition described in DMM is proposed by Ziegler [8]. Kalyan Kumar [9] and Prasad [10] have developed an

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continuum instability criterion which is given by

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln[m/(m+1)]}{\partial \ln \dot{\varepsilon}} + m < 0 \qquad (2)$$

where $\dot{\varepsilon}$ is the strain rate. The variation of dimensionless parameter $\xi(\dot{\varepsilon})$ with temperature and strain rate constitutes an instability map. Typical metallurgical instabilities are mainly adiabatic shear bands formation and flow localization. The continuum criterion has been applied to a large number of various materials and predictions were validated by microstructural examination of deformed specimens [11].

2. Experimental procedures

The chemical composition (wt.%) of the material used in the present investigation was as follows: Cr, 19.82; W, 18.48; Mo, 1.24; Al, 0.46; C, 0.11; B, 0.0028; La, 0.026 P, S <0.004, Bal. Ni. The cast material was prepared by vacuum induction melting (VIM) and vacuum arc re-melting (VAR). The ingot was homogenized at 1200 °C for 24 h and furnace cooled. Cylindrical specimens of 8 mm diameter and 12 mm height were machined from the homogenized ingot and used for compression testing. Compression tests were carried out in the temperature range 1000–1200 °C at intervals of 50 °C and in the constant true strain rate range of 0.001–10 s^{-1} at intervals of one order of magnitude. Isothermal compression tests were conducted on Gleeble-1500D thermomechanical simulator testing machine. The temperature control was within ±1 °C. The adiabatic temperature rise in the specimen during testing was measured by a fine thermocouple wire embedded in a 1-mm hole machined up to the center at mid height of the specimen. All the samples were resistance heating up to the deformation temperatures at which it was held for 5 min to eliminate the thermal gradient before deformation, then the samples were deformed to total true strain of about 0.9. After hot deformation, the samples were quenched in water to freeze microstructure. Tantalum foil of 0.1 mm thick was used between the specimen and the dies to avoid welding of the specimen to the dies during hot deformation testing. The deformed specimens were sectioned parallel to the compression axis and the cut surface was prepared for metallographic examination using standard procedures. The polished specimens were etched with aqua regia ($HCl:HNO_3 = 3:1$) to reveal the microstructure. Etching times varied with test conditions and varied from 50 s to 3 min. The average recrystallized grain size was determined using the line intercept method. It should be noted that the location of microstructure observation of deformed samples in this paper was referred in literature [12].

At the end of the test, the load-stroke data were converted into the true stress–true strain curves using standard equations. The flow stress data were corrected for adiabatic temperature rise using a procedure described elsewhere [13]. A cubic spline fit between log flow stress and log strain rate was used to calculate m as a function of strain rate. This was repeated for the various temperatures. The efficiency of power dissipation η was then calculated as a function of temperature and strain rate using Eq. (1) and plotted as an iso-efficiency contour map. The data were also used to evaluate the instability parameter by means of Eq. (2) as a function of temperature and strain rate to obtain an instability map.

3. Results and discussion

3.1. Cast and homogenized microstructure

The initial microstructure of as-cast Ni–Cr–W superalloy is shown in Fig. 1, which is a typical dendritic structural with a large average grain size of about 320 μm. Optical metallography (Fig. 1) reveals that many of carbide particles dispersively distribute in the γ austenite matrix. XRD analysis (Fig. 2) identified that the particles are tungsten-rich primary carbides of the M_6C-type and chromium-rich $M_{23}C_6$-type carbides.

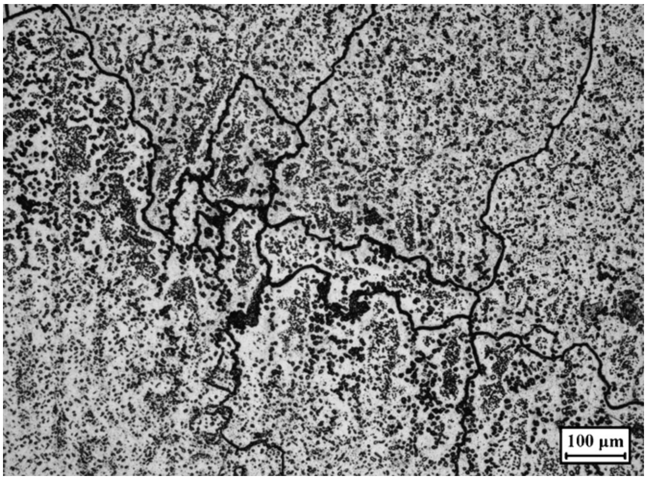

Fig. 1. Initial microstructure of cast and homogenized Ni–Cr–W superalloy.

3.2. Flow behavior

Typical flow curves obtained at 1000 and 1150 °C and at different strain rates are shown in Fig. 3a and b, respectively. The curves of strain rate 10 s^{-1} are corrected for adiabatic heating rise. This correction was done using a liner interpolation between $\ln(\sigma)$ and $(1/T)$ [13]. At lower strain rates ($\leq 1\ s^{-1}$), the adiabatic temperature rise was not significant and the curves need no correction. At strain rates $\leq 0.1\ s^{-1}$, the flow curves exhibit flow softening after reached a peak stress, followed by a steady-state flow stress at the large strains. This type of flow behavior is indicative of DRX [14,15]. At higher strain rates, the flow curves exhibit continuous flow softening characteristic which is more significant at the lower temperatures and higher strain rates. The continuous flow softening at higher strain rates may be attributed to dynamic recrystallization or flow instability [7]. Hence, it is not very appropriate to predict the deformation mechanisms from the shape of the flow curves alone. Further analysis is required to confirm these mechanisms. It is interesting to note that flow curve obtained at 1150 °C and 10 s^{-1} reveals the existence

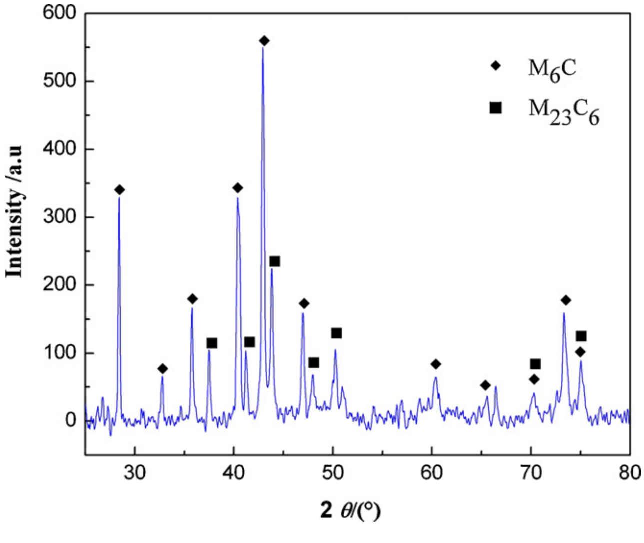

Fig. 2. X-ray diffraction patterns of electrolytically extracted residue of as-cast Ni–Cr–W superalloy.