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Materials Characterization 58 (2007) 220–225

MATERIALS CHARACTERIZATION

Dissolution kinetics of δ phase and its influence on the notch sensitivity of Inconel 718

Dayong Cai *, Weihong Zhang, Pulin Nie, Wenchang Liu, Mei Yao

State key Laboratory of Metastable Materials Science and Technology, Yanshan University, 066004, Qinhuangdao, People's Republic of China

Received 4 January 2006; received in revised form 21 April 2006; accepted 22 April 2006

Abstract

The dissolution kinetics of δ phase in Inconel 718 at 980 °C, 1000 °C and 1020 °C and its influence on high temperature notch sensitivity have been studied using a quantitative X-ray diffraction (XRD) method and high temperature stress rupture life tests of notched specimens. The amount of δ phase decreases gradually during holding time at 980 °C, 1000 °C and 1020 °C. The δ phase will be fully dissolved in the austenitic matrix at 1020 °C for more than 2 h. A certain amount of δ phase still exists after holding at 980 °C and 1000 °C for times up to 6 h; the amount remaining are 3 wt.% and 0.6 wt.%, respectively. The dissolution rate remains at a high level at the beginning, and then decreases gradually with an increase of holding time. A dynamic equilibrium state can be approached after holding at 980 °C for more than 30 min and at 1000 °C for more than 2 h. The alloy with δ phase amounts higher than 0.62 wt.% does not exhibit notch sensitivity, whereas serious notch sensitivity exists if the concentration is below 0.43 wt.%.

Keywords: Inconel 718; δ phase; Dissolution kinetics; Notch sensitivity

1. Introduction

The Ni–Fe base superalloy Inconel 718, which is age-hardened by combined precipitation of fine γ′ and γ″ phases in an austenitic matrix, has been widely used for high temperature services such as gas turbine disks [1,2]. The precipitation of intermetallic phases in Inconel 718 has been intensively studied. It has been found that the major hardening phase is the metastable γ″ phase which goes to the δ phase in equilibrium. All these three phases are of the A_3B type: the γ″ and δ phases are based on the composition Ni_3Nb and the γ′ phase on the composition $Ni_3(AlTi)$. The amount of precipitation phases, together with their shape and distribution, has a determining influence on the mechanical properties. Considerable research has been carried out on the strengthening effects of the γ′ and γ″ phases and the toughening effects of δ phase in order to improve the overall mechanical properties. It is widely accepted that δ phase has important effects on the microstructure and mechanical properties [3,4]. Recently, grain size control in "Delta Processed" Inconel 718 and the influence of δ phase on high temperature notch sensitivity and impact toughness have been studied [5,6]. The results indicate that δ phase can form in the alloy during processing or in service, generally

* Corresponding author.
E-mail address: dayongcai@sina.com.cn (D. Cai).

1044-5803/$ - see front matter
doi:10.1016/j.matchar.2006.04.020

appearing in plate-shaped or globular morphology. Controlled precipitation of the δ phase at grain boundaries is believed to have beneficial effect on the stress rupture ductility, and can also inhibit the growth tendency of the austenitic grains during the forging process. The δ phase will partly be dissolved into the austenitic matrix during the hot working. As far as the controlled precipitation is concerned, the precipitation and dissolution behavior are the two most important aspects, but little work has been performed on the latter aspect.

The goals of the present work are to analyze the dissolution behavior of δ phase and to determine its effects on the high temperature notch sensitivity of Inconel 718.

2. Materials and experimental methods

2.1. Materials and heat treatment

Hot rolled bars of Inconel 718 with an average grain size of about 20 μm were chosen for the dissolution behavior analysis. The chemical composition is listed in Table 1. Solid solution annealing was performed at 980 °C for 3 h followed by air cooling. A δ phase ageing treatment (890 °C for 20 h) was carried out to insure adequate amounts of δ phase in the austenitic matrix for dissolution analysis. Dissolution treatments were performed at 980 °C, 1000 °C and 1020 °C.

2.2. X-ray diffraction quantitative phase analysis

According to the accepted phase transformations of Inconel 718, γ phase, δ phase and NbC are the three main phases after the initial solution annealing treatment. The amount of δ phase can be directly determined using X-ray diffraction (XRD) by a comparison of the integrated intensity of the diffraction peaks. The samples for XRD quantitative analysis were mechanically polished followed by chemical etching. Quantitative analysis was performed in D/max-rB X-ray diffractometer with Cu Kα radiation. The calculation equations are as follows; for detail see Ref. [7]:

$$W_{\mathrm{NbC}} + W_{\delta} + W\gamma = 1 \tag{1}$$

$$\frac{W_{\gamma}}{W_{\delta}} = \frac{\rho_{\gamma}}{\rho_{\delta}} \cdot \frac{\frac{1}{n} \cdot \sum_{i}^{n} (I_i^{\gamma}/R_i^{\gamma})}{\frac{1}{m} \sum_{i}^{m} (I_i^{\delta}/R_i^{\delta})} \tag{2}$$

$$\frac{W_{\mathrm{NbC}}}{W_{\delta}} = \frac{\rho_{\mathrm{NbC}}}{\rho_{\delta}} \cdot \frac{I_{111}^{\mathrm{NbC}}/R_{111}^{\mathrm{NbC}}}{\frac{1}{m} \sum_{i}^{m} (I_i^{\delta}/R_i^{\delta})} \tag{3}$$

where W_{NbC},W_{δ} and W_{γ} are the amount of the NbC, δ and γ phases in weight percent, ρ_{NbC}, ρ_{δ}, ρ_{γ} are the volume density of NbC, δ and γ phases, and I_{111}^{NbC}, I_i^{δ}, I_i^{γ} are the integrated intensities from NbC, δ and γ phases, respectively. The terms m and n are the number of selected diffraction peaks, and R_i can be expressed as:

$$R_i = \frac{1}{v^2} P_i F_i^2 \varphi(\theta) e^{-2M} \tag{4}$$

where v is the precise volume of the unit cell, P_i is the multiplicity factor of diffracting plane, F_i is the structure factor, $\psi(\theta)$ are the Lorentz and polarization factors, and e^{-2M} is the temperature factor. The structure factor, F_{hkl}, associated with the δ phase has been given by Sundararaman et al.[8], and the values of F_{hkl} can be calculated according to the composition of the δ and γ phases.

2.3. High temperature notch sensitivity and room temperature mechanical properties

Six samples with different amounts of δ phase after the dissolution treatments were selected to perform a standard double ageing treatment (720 °C × 8 h + furnace cooling at 55 °C/h to 620 °C × 8 h, then air cooling). The high temperature notch sensitivity tests were conducted at 650 °C at a stress level of 700 MPa. Combined notch specimens were selected for the notch sensitivity analysis and the sample dimension is shown in Fig. 1. The cross-section size is identical at the notched location and the smooth location. For this type of combined notch specimen, the material is considered to be notch sensitive when failure occurs at the notch position and the stress rupture life is less than 25 h. In

Table 1
Chemical compositions of Inconel 718 alloy, (wt.%)

C	Cr	Ti	Ni	Mo	Nb+Ta	Al	B	Fe	Mn	Si	S	P
0.032	18.8	1.05	53.28	2.97	5.12	0.58	0.002	bal.	0.13	0.09	0.002	0.005