Materials Science and Engineering A 418 (2006) 229–235

MATERIALS SCIENCE & ENGINEERING A

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# Influence of pre-compression on microstructure and creep characteristic of a single crystal nickel-base superalloy

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Accepted 21 November 2005

**Abstract**

The P-type γ′ rafted structure of a nickel-base single crystal superalloy with [0 0 1] orientation is formed by means of the pre-compressive stress treatment. An investigation has been made to detect the microstructure evolution and creep features of a single crystal nickel-base superalloy by means of the measurement of creep curves and SEM observation. Results show that creep resistance of alloy with the P-type structure exhibits a marked sensitivity of the applied stress and temperature. When the temperature is lower than 1000 °C under the applied stress of 200 MPa, compared with the alloy with the cuboidal γ′ phase, the P-type rafted structure alloy possesses both a lower minimum creep rate and longer rupture lifetime. When the applied temperature is higher and the applied stress is larger, the properties of the alloys are worsened. This indicates that the P-type rafted structure is beneficial to improving creep resistance of the alloy under the conditions of lower temperature and stress. Compared with the cuboidal γ′ phase alloy, the microstructure evolution of the P-type structure alloy occurs in the steady state of tensile creep. The P-type γ′ rafted structure in the alloy is gradually broken up, and twisted along the ⟨1 1 0⟩ orientation as creep goes on. After crept up to fracture, the twisted γ′ phase is coarsened, and transformed into the microstructure that the rafted γ′ phase is rearranged along the direction roughly perpendicular to the applied stress axis.


*Keywords:* Single crystal nickel-base superalloy; Pre-compressive stress treatment; P-type γ′ structure; Tensile creep; Microstructure evolution

## 1. Introduction

Ni-base single crystal superalloys are widely used for production of turbine blades because of their excellent resistance against high temperature creep, which is derived from the high volume fractions of γ′ strengthening phase and the regular array of the cuboidal γ′ precipitate. The creep behavior is closely related to their microstructures. Many experiments indicate that the transverse rafted structure (N-type) tends to be formed at relatively high temperatures under a lower tensile stress for the negative lattice misfit alloys. But, under the conditions of the applied compressive stress, the longitudinal plate-like γ′ rafted structure (P-type) is formed along the direction parallel to the stress direction [1]. The γ′ rafted structure has been believed to enhance the creep resistance of alloy [2]. However, the microstructure evolution of alloy leads, in most cases, to deteriorated creep properties. The effects of the modified microstructure on the creep and fatigue behavior have been discussed controversially in many papers [3,4]. Ott and Mughrabi [5] had reported some experimental results about the effects of microstructure on creep properties, which shows that a N-type raft structure has caused a deterioration of the elevated temperature fatigue behavior. In contrast, an improvement of the fatigue behavior is found in a P-type raft structure alloy. Several authors [6] pointed out that a N-type raft structure alloy enhances the creep resistance of the superalloy under the condition of high temperatures and very low stresses, in the case of comparably high stresses and elevated temperature, which can lead to an increase of the creep rate. Schneider et al. [7] found that CMSX-4 alloy which transformed into N-type rafts structure by means of pre-tensile stress treatment leads to the deterioration of creep properties at 800 and 950 °C. but it increases creep strength of CMSX-4 alloy at 1100 °C. As a result of much more investigations focused on the influence of a N-type raft structure on the creep properties of alloy, the influence of a P-type raft structure on the creep properties of alloy is still not clear.

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doi:10.1016/j.msea.2005.11.028

In the paper, a single crystal nickel-base superalloy is pre-compressively treated to form a P-type rafted structure. Compared with the initial cuboidal γ′ structure alloy, the influences of a P-type rafted structure on the microstructure and creep properties of alloy are investigated.

## 2. Experimental procedure

A single crystal nickel-base superalloy with [0 0 1] orientation has been produced by means of crystal selection method in a vacuum directional solidification furnace under a high thermal gradient. All specimens were within 10° deviating from [0 0 1] orientation. The chemical composition of the superalloy is listed in Table 1. The standard heat treatment of all specimens is given as follows: 1300 °C, 4 h, AC + 1100 °C, 4 h, AC + 870 °C, 16 h, AC. The tensile samples were cut along the [0 0 1] orientation, with cross-section of 3.4 mm × 2 mm and the gauge length of 30 mm, the wider surface of the samples was parallel to the (1 0 0) crystal plane.

In order to receive a P-type γ′ rafted structure alloy, some specimens were pre-compressively treated for 6 h at 1050 °C in $10^4$ Pa vacuum with a stress of 200 MPa, in which a smaller strain was kept to avoid the damage of the structure in the alloy. The accumulated creep strain was 0.32%. In the experiment, two sets of A and B structure specimens were prepared. The specimens with an initial cuboidal γ′-structure were defined as the alloy with A structure, while the specimens with the γ′ raft structure parallel to the stress axis were defined as the alloy with B structure. Uniaxial constant load tensile creep testing was carried out in a FC-20 creep testing machine, under the conditions of the applied loading range from 200 to 280 MPa and applied temperatures range from 980 to 1020 °C. The strain data were measured at regular intervals with an extensometer. The tensile tests were interrupted at different times, and the samples were cooled in the furnace under loading to preserve the dislocation arrangement.

Microstructures of the alloys were observed under a Cambridge S-360 scanning electron microscopy. Samples for TEM observation were prepared by twin-jet thinning in a solution containing 8 vol.% perchloric acid and methanol at −25 °C.

Table 1
Chemical composition of the alloy (wt.%)

| | |
|---|---|
| Al | 5.47 |
| Ti | 2.14 |
| Cr | 8.39 |
| W | 9.47 |
| Ta | 2.92 |
| C | 0.014 |
| P | 0.002 |
| Ni | Balance |

## 3. Results and analysis

### 3.1. Microstructures of alloy with different structures

Fig. 1(a) is a morphology of the alloy at fully heat treatment state, which consists of the cuboidal γ′ precipitates embedded coherently in γ matrix, and γ′ phase aligned regularly along the ⟨1 0 0⟩ orientation. This shows that the cuboidal γ′ precipitate possesses a volume fraction of about 65%, and an average size of about 450 nm and separated by thin γ channels about 50 nm. The lattice misfit was determined by high resolution X-ray diffraction as $\delta \approx -1.4 \times 10^{-3}$ [8]. Fig. 1(b) illustrates that the cuboidal γ′ phase has been transformed into a typical rafted structure along the direction parallel to the applied stress axis after alloy crept for 6 h under the compressive stress of 200 MPa at 1050 °C.

### 3.2. Creep features of alloy with different structures

In order to investigate the effect of γ′ phase morphology on creep behavior of the alloy, the tensile creep testing of the alloy with different structures are conducted in the temperature range 980–1020 °C. Fig. 2 shows the typical creep curves of the alloy with A structure, which displays a feature of possessing different creep stages, including the primary, steady-state and tertiary creep stages. The lifetime of the alloy crept up to fracture is about 200 h, which is decreased with the increase of creep temperature as shown in Fig. 2(a). Although the strain values of the primary creep stage are smaller as shown in Fig. 2(b), the primary creep rates are continuously decreased as creep goes on, and then the creep displays out a feature of the steady-state creep stage in

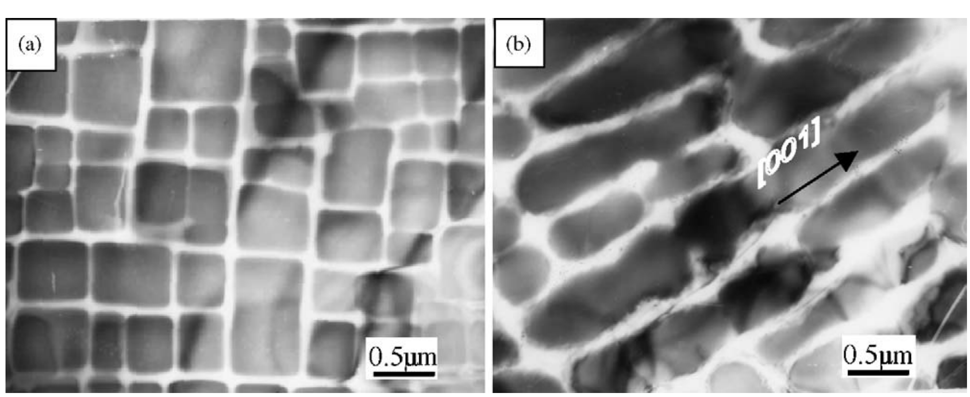


Fig. 1. Microstructures of the alloy at different treatment states. (a) Cuboidal γ′ phase embedded in γ matrix after standard heat treatment and (b) after compressive creep treatment at 1050 °C and 200 MPa for 6 h.