Research on the creep mechanism of a Ni$_3$Al-based single crystal superalloy IC6SX under 980°C/205MPa

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Abstract. The Ni$_3$Al-base single crystal superalloy IC6SX used in this work was prepared by spiral grain selection method. And the creep behaviors of the IC6SX alloys was studied systematically under 980°C/205MPa. The microstructure evolution, movement of dislocations, formation of the dislocation networks and dislocation configuration for the alloy during the creep process were investigated by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). It has been found that the creep performance of the single crystal alloy IC6SX is excellent under the condition of 980°C/205MPa. The results showed the creep mechanism included dislocation slipping and diffusion for Ni$_3$Al-based Single Crystal Superalloy IC6SX under 980°C/205MPa.

Keywords: Ni$_3$Al, IC6SX, Creep mechanism, Dislocation configuration

1. Introduction

As the important materials for the aero-engine, single crystal superalloys have been widely used for the turbine blades and vanes. At present, with the development of advanced aero-engine, the maximum service temperature of the turbine blades has been reached to the temperature range of 1100-1200°C (90% of the melting points of Ni-based superalloys). It is urgent to develop a new kind of blades material for the advanced engine [1]. As the candidate materials for the turbine blades, a new type of Ni$_3$Al base single crystal alloy IC6SX consisted of Ni, Al, Mo and B was developed, and it has higher melting temperature, lower density and cost compared with the single crystal Ni-based superalloys and excellent high temperature performance. For the single crystal superalloys, the high temperature creep performance is one of the important performance characteristics [2]. Much relevant work has been reported in these filed for different alloy system [3-10]. In order to clarify the mechanism of creep deformation and fracture for the alloy IC6SX, the creep properties of the IC6SX alloy were investigated under 980°C/205MPa. This work will lay a solid foundation for the engineering application of the IC6SX alloy.

2. Experimental Methods
The Ni\(_3\)Al-based single crystal superalloys IC6SX used in this work were prepared by screw selection crystal method in DZG-0.025 directional solidification furnace. And its composition is 7.4–7.8 wt% Al, 14 wt% Mo, 0.03 wt% B and Ni as balance. And the orientation of the IC6SX alloys was observed by back scatter Laue method. The single crystal bars with (001) direction without defect were selected for creep tests. And the creep tests under 980°C/205MPa were carried out in a GWT304 high temperature creep testing machine. The microstructure and dislocation configuration were investigated by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) after the creep tests.

3. Results and Discussion
The as-cast microstructure of the single crystal alloy IC6SX and the microstructure after heat treated under the conditions of 1280°C/10h+870°C/32h were described in figure 1 (A) and (B), respectively. As shown in figure 1, it can be found that, compared with the as-cast microstructure, the γ\(^\prime\) phase with the cuboidal shape were finer and distributed homogeneously. The sizes of the re-precipitated γ\(^\prime\) particles are about 0.8 μm after heat treatment (1280°C/10h+870°C/32h).

![Figure 1](image-url)

**Figure 1.** The microstructure of the single crystal alloy IC6SX A. The as-cast. B. After heat treatment.

The creep curve of the single crystal alloy IC6SX under 980°C/205MPa was given in figure 2. As shown in figure 2, it can be found that the creep curve of the Ni\(_3\)Al-based single crystal superalloy IC6SX was consisted of three stages, including decelerating creep stage, steady-state creep stage and accelerated creep stage. The creep performance data of the single crystal alloy IC6SX under 980°C/205MPa was given in table 1. As can be seen from table 1, at the decelerating creep stage, the creep rate decrease gradually with the increase of stress and the holding time was less than 1 hour at this stage. At the steady-state creep stage, the steady-state creep rate was only \(3.65 \times 10^{-7}\) (%/S) and the holding time increased to some extent but also less than 27 hours. However, at the accelerated creep stage, the holding time reached more than 94 hours. According to the creep curves of the IC6SX alloy as shown in figure 2, it can be revealed that the most creep strain during the processing of the creep test was consumed at the accelerated creep stage. The creep life of the single crystal IC6SX alloy was 121.47 hours under 980°C/205MPa. And the single crystal alloy IC6SX has excellent creep performance under 980°C/205MPa.
Figure 2. The creep curve of the single crystal alloy IC6SX under 980°C/205MPa.

Table 1. The creep performance data of the single crystal alloy IC6SX under 980°C/205MPa.

| Creep Performance                        | Creep Stress | 205MPa  |
|------------------------------------------|--------------|---------|
| Instantaneous elastic strain (%)         |              | 0.223   |
| The plastic strain of decelerating creep stage (%) |              | 0.131   |
| The time of decelerating creep stage (h)  |              | 0.84    |
| The plastic strain of steady-state creep stage (%) |              | 0.344   |
| The time of steady-state creep stage (h)  |              | 26.15   |
| The steady-state creep rate(%) / S       |              | 3.65 x 10^{-6} |
| The plastic strain of accelerated creep stage (%) |              | 22.637  |
| The time of accelerated creep stage (h)  |              | 94.48   |
| The creep life (h)                       |              | 121.47  |

The microstructure morphology of the IC6SX alloy at the different creep stages under 980°C/205MPa was investigated as shown in Figure 3. As seen from Figure 3(A), the microstructure of the alloy IC6SX at the decelerating creep stage was similar to that after heat treatment and the \( \gamma' \) phase was with cubic shape. At the steady-state creep stage, the microstructure of \( \gamma \) phase was still grid structure as described in Figure 3 (B). But the \( \gamma' \) phase with cubic shape decreased. However, at the accelerated creep stage, a part of the grid structure of \( \gamma \) phase was destroyed and the \( \gamma' \) phase shaped cubic was decreased further compared with that at the other two stages. The raft microstructure has not been formed yet.
Figure 3. SEM images of Alloy IC6SX at the different creep stages under 980°C/205MPa.
A. The decelerating creep stage. B. The steady-state creep stage. C. The accelerated creep stage.

Figure 4. Dislocation configuration of the different creep stages of the single crystal alloy IC6SX under 980°C/205MPa.
A. The decelerating creep stage, B. The steady-state creep stage, C. The accelerated creep stage.
The dislocation patterns during the different creep stages for the IC6SX alloy under 980°C/205MPa were illustrated as given in figure 4. From figure 4(A), it has been found that the dislocation proliferation happened in the γ phase and the dislocations did not cut γ' phase at the decelerating creep stage. With the progress of creep, the dislocation proliferation in the γ phase was going on so that the dislocation density increased. Meanwhile, the dislocation networks appeared on the interface between γ and γ' phases. The dislocation networks inhibited the dislocation motion and resulted in the strengthening effect simultaneously. At the steady-state creep stage, the tensile stress was near equivalent to dislocation resistance. And a small amount of dislocations cut the γ' phase leading to the γ' phase appearing slow deformation. So that the stress balance was broken when the number of the dislocations cutting γ' phase increased and the dislocation network was destroyed. Finally, at the accelerated creep stage, the strength of γ' phase decreased as a lot of dislocation cut the γ' phase until the single crystal alloy IC6SX occurred fracture. Under the condition of 980°C/205MPa, the temperature is higher and the atomic diffusion rate was faster in the alloy. So that, at 980°C/205MPa, the creep mechanism of single crystal superalloys IC6SX was not only the dislocation glide but also diffusion mechanism.

4. Conclusions

1. The creep life was 121.47 hours for the single crystal alloy IC6SX under 980°C/205MPa. The steady-state creep rate was only 3.65×10^-6(%/S). And the time of the accelerated creep stage was more than 94 hours.

2. At the decelerating creep stage, the microstructure morphology of the γ' phase for IC6SX alloy was cubic and no raft microstructure has been found. Meanwhile, the dislocation proliferation happened in the γ phase and the dislocations did not cut γ' phase. With the progress of the creep, the dislocation constantly cut γ' phase and the strength γ' phase decreased due to the dislocation network was destroyed.

3. At 980°C/205MPa, the temperature is higher and the atomic diffusion rate was faster in the alloy. The deformation of alloy was caused by not only dislocation glide but also atomic diffusion. So that the creep mechanism included dislocation glide mechanism and diffusion mechanism.

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