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Research Article

Effect of Stress on Creep Behavior of Single Crystal Alloy IC6SX at 980°C

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Ni_3Al-based single crystal alloy IC6SX was prepared by seed crystal method. The effect of different stress conditions on creep behavior of this alloy at 980°C was investigated. The results showed that the creep life of this alloy at 980°C decreased significantly with the increase of stress. When the stress increased from 180 MPa to 230 MPa, the creep life dropped from 245.5 h to 69.3 h, and the steady-state creep rate increased slightly but not significantly. Meanwhile, the morphology of γ' phase and dislocation after creep were studied. The results showed that with the increase of stress, the density of dislocations in the γ' phase increased gradually, the strength of this alloy decreased gradually, so the creep life decreased significantly. The Y-NiMo phase resolved from the γ phase decreased gradually as the creep life decreased. The creep experiment of the alloy was carried out at 980°C. Due to the higher temperature, the diffusion of atoms in this alloy became faster. Deformation was not only caused by the slippage of dislocations in the crystal but also by the diffusion of atoms. Therefore, the creep mechanism of single crystal alloy IC6SX at this temperature is a mixed mechanism of dislocation glide and diffusion.

1. Introduction

With the rapid development of modern aviation technology, the requirements for the turbine inlet temperature and thrust-to-weight ratio of gas turbine engines are improved constantly, so the properties of the alloys used in aeroengines should also be improved [1]. Compared with nickel-based single crystal alloy, Ni_3Al-based single crystal alloy has the advantages of low density, high melting point, large specific strength, high plasticity, low cost, long service life, good mechanical properties at high temperature, and strong oxidation resistance. Therefore, the research and development on Ni_3Al-based single crystal alloys have been becoming a research hotspot in the field of high-temperature structural materials [2–5].

American scientists have developed many Ni_3Al-based superalloys such as IC50, IC218, and IC221M [6]. The researches in the field of materials have achieved certain results on Ni_3Al-based materials during the last decades, and several Ni_3Al-based superalloys with excellent properties have been developed for turbine blades and vanes of aeroengines, such as IC6, IC6A, IC10, and IC6SX [7–9]. And the single crystal Ni_3Al-based superalloy IC6SX has been developed on the basis of DS IC6 which is the directionally solidified alloy with similar contents for further increasing mechanical properties [10]. IC6SX has low density, high initial melting point, high-temperature durable strength, low cost, and good comprehensive properties [11, 12]. The result of Kong and Li [13] showed that the dislocation configuration and movement pattern of Ni_3Al-based single crystal alloy IC6SX are different under the different temperature and stress conditions. The result of Zhang et al. [14] showed that the creep mechanisms are dislocation glide at lower testing temperatures in higher stress levels and dislocation climb at higher temperatures in lower stress levels.

It can be seen that material workers have carried out a lot of research on the creep behavior of nickel-based single crystal alloys, and many new developments have been made.

Table 1: Creep properties of single crystal alloy IC6SX at 980°C.

Creep stress Creep properties	180 MPa	205 MPa	230 MPa
Instantaneous elastic strain (%)	0.206	0.223	0.252
Plastic strain during deceleration creep stage (%)	0.089	0.131	0.14
Deceleration creep stage time (h)	0.95	0.84	0.56
Plastic strain during steady-state creep stage (%)	0.776	0.549	0.518
Steady-state creep stage time (h)	129.53	41.81	14.61
Steady-state creep rate (%/S)	1.66×10^{-6}	3.65×10^{-6}	9.85×10^{-6}
Plastic strain during accelerated creep stage (%)	35.035	22.637	38.386
Accelerated creep phase time (h)	115.02	78.82	54.13
Creep life (h)	245.5	121.47	69.3

However, the scientific problem of how different stress conditions affect the creep behavior of Ni_3Al-based single crystal alloy IC6SX remains unsolved.

In this paper, Ni_3Al-based single crystal alloy IC6SX specimens were prepared by seed crystal method [15]. And the effect of different stress conditions on creep behavior of this alloy at 980°C was explored. This experiment has never been studied before, and it is also the innovative point of this work. The creep mechanism of IC6SX at 980°C was found out by comparing the changes in properties, microstructures, and dislocations of single crystal alloys during creep process under different stress conditions, providing a theoretical basis for the application of Ni_3Al-based single crystal alloy.

2. Experimental Procedure

The material used for the present study was a Ni_3Al-based alloy IC6SX, with a nominal composition of Ni-7.4~8.0Al-13.5~14.3Mo-0.02~0.03B (wt%). The raw materials used were all high-purity elements, including Ni (99.9%), Al (99.9%), and Mo (99.9%). Firstly, the master alloy ingot with a size of $\varphi 75 \times 500$ mm was prepared by vacuum induction melting method in the GVR-100 vacuum induction furnace. Then, the single crystal alloy test bars with different crystal orientations were prepared by seed crystal method in the DZG-0.025 directional solidification furnace, and the size of the test bars was $\varphi 15 \times 160$ mm. All the test bars were calibrated for crystal orientation by X-ray backscattering Laue method. The test bars with orientation deviation less than 5° and without defects were selected for this study.

The heat treatment conditions of IC6SX test bars were 1260°C/10 h air cooling solution treatment +870°C/32 h air cooling aging treatment. Then, they were machined into creep specimens and placed in the GWT504 high-temperature endurance creep testing machine, maintaining a temperature environment of 980°C, and uniaxial constant-load tensile creep tests were performed under 180 MPa, 205 MPa, and 230 MPa stress conditions, and the creep data were obtained.

The microstructure of the specimens was analyzed by an optical microscope (OM) and a scanning electron microscope (SEM). The morphology and evolution of dislocation were observed by the Tecnai F30 field emission transmission electron microscope.

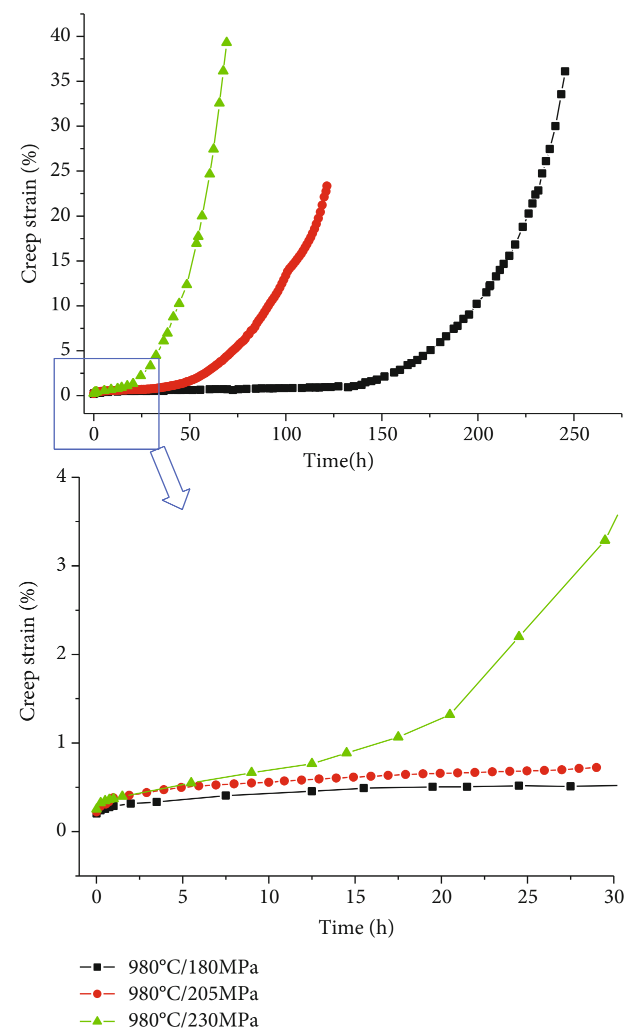
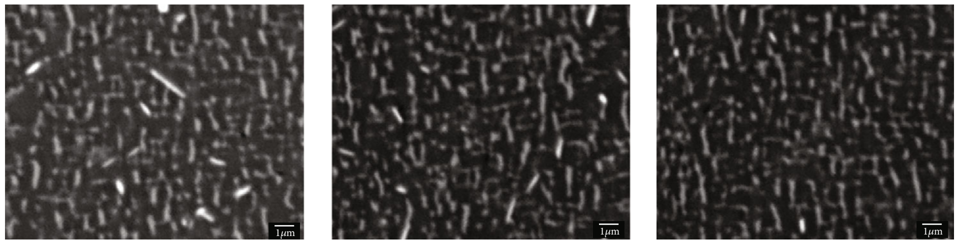


Figure 1: Creep curve of single crystal alloy IC6SX at 980°C.

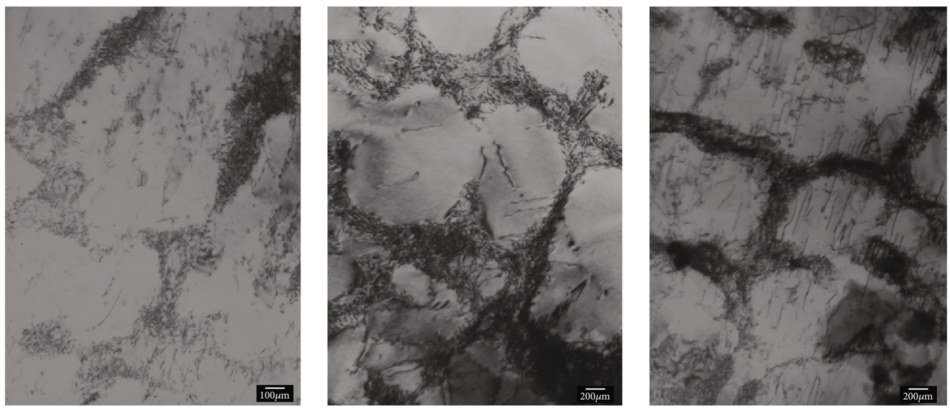
3. Results and Discussion

3.1. Creep Properties of Single Crystal Alloy IC6SX at 980°C. All the creep property parameters of single crystal alloy IC6SX under the three stress conditions of 180 MPa, 205 MPa, and 230 MPa at 980°C are shown in Table 1.



(a) (b) (c)

Figure 2: Microstructure of single crystal alloy IC6SX after creep at 980°C: (a) 180 MPa, 245.5 h; (b) 205 MPa, 121.47 h; (c) 230 MPa, 69.3 h.



(a) (b) (c)

Figure 3: Dislocation structure morphology of single crystal alloy IC6SX after creep at 980°C: (a) 180 MPa, 245.5 h; (b) 205 MPa, 121.47 h; (c) 230 MPa, 69.3 h.

Figure 1 shows the creep curves of single crystal alloy IC6SX under three different stress conditions at 980°C. From Figure 1, it can be identified that the creep curves of this alloy under three stress conditions can be divided into deceleration creep stage, steady-state creep stage, and accelerated creep stage. All the deceleration creep stage times of this alloy under three stress conditions were short and still less than 1 h to the end. As the stress increased from 180 MPa to 230 MPa, the duration of the steady-state creep stage decreased from 129.53 h to 14.61 h. When the stress was 180 MPa, the alloy entered the steady-state creep stage of 129.53 h after the deceleration creep stage of 0.95 h, the creep strain was 0.776%, and the steady-state creep rate was 1.66 $\times 10^{-6}$ (%/S). Then, it entered the accelerated creep stage of 115.02 h, and the final creep life was 245.5 h. When the creep stress increased to 205 MPa, the steady-state creep stage duration of the alloy decreased rapidly to 41.81 h, the creep strain was 0.549%, and the steady-state creep rate increased to 3.65×10^{-6} (%/S), increased by more than 1 time. Then, the alloy entered the accelerated creep stage of 78.82 h; the creep life of the alloy under this stress was 121.47 h. When the creep stress continued to increase to 230 MPa, the steady-state creep stage duration of the alloy decreased to 14.61 h, the creep strain was 0.518%, and the steady-state creep rate continued to increase to 9.85×10^{-6} (%/S), the creep life was only 69.3 h.

The results showed that the creep life and steady-state creep stage duration of single crystal alloy IC6SX at 980°C decreased significantly with the increase of stress. When the stress increased from 180 MPa to 230 MPa, the creep life decreased from 245.5 h to 69.3 h. The duration of the creep stage dropped from 129.53 h to 14.61 h. But with the increase of stress, the change of creep strain was not significant, and the steady-state creep rate increased slightly but not significantly. To analyze the reasons for these results, it is necessary to further study the structure and dislocation morphology of the alloy after creep.

3.2. Creep Structure Evolution of Single Crystal Alloy IC6SX at 980°C

3.2.1. Morphology of γ' Phase after Creep at 980°C. Figure 2 shows the microstructure of single crystal alloy IC6SX after creep under different stress conditions at 980°C. It can be identified that the degree of cubicization of the γ' phase reduced significantly under the three stress conditions. Due to the diffusion of atoms in the single crystal alloy, a typical directional coarsening of the γ' phase was formed. The network structure was damaged severely and disconnected by the γ' phase; most of the γ' phase had been connected. The creep life decreased with the increase of stress, and the Y-NiMo phase precipitated from the γ phase decreased gradually.

3.2.2. Morphology of Dislocation after Creep at 980°C. Figure 3 shows the morphology of dislocation after creep under different stress conditions at 980°C. When the stress was 180 MPa, since the creep life was as high as 245.5 h, both γ and γ' phases underwent severe directional coarsening.

There was a high-density dislocation network in the γ phase, some dislocations cut into the γ' phase, but the dislocation density in the γ' phase was not high. When the stress increased to 205 MPa, the high-density dislocation network in the γ phase was still there, and some dislocation pairs cut into the γ' phase. As the stress increased to 230 MPa, a large number of dislocation pairs cut into the γ' phase and crossed each other, and the density of dislocations increased. As a result, the strength of this alloy decreased, so the creep life was only 69.3 h.

3.3. Analysis and Discussion. Meanwhile, the morphology of the γ' phase and dislocation after creep were studied. The results showed that with the increase of stress, the dislocations cut from the γ phase into the γ' phase increased gradually, so the dislocation network density in the γ phase decreased gradually. The density of dislocations in the γ' phase increased gradually, and the dislocations crossed each other. As a result, the strength of this alloy decreased gradually, so the creep life decreased significantly.

The creep experiment of the alloy was carried out at 980°C. Due to the higher temperature, the diffusion of atoms in this alloy became faster. A typical directional coarsening of the γ' phase was formed, the dislocation network in the γ phase was destroyed by the γ' phase, and the organizational evolution had occurred. So the deformation was not only caused by the slippage of dislocations in the crystal but also by the diffusion of atoms. Therefore, the creep mechanism of single crystal alloy IC6SX at this temperature is a mixed mechanism of dislocation glide and diffusion.

4. Conclusions

In this paper, Ni_3Al-based single crystal alloy IC6SX was taken as the research object. The effect of different stress conditions on creep behavior of this alloy at 980°C was explored. The creep mechanism of IC6SX at 980°C was found out by comparing the changes in properties, microstructures, and dislocations of single crystal alloys during creep process under different stress conditions, providing a theoretical basis for the application of Ni_3Al-based single crystal alloy. The main conclusions are as follows:

(1) The creep life of single crystal alloy IC6SX at 980°C decreased significantly with the increase of stress

(2) When the stress increased from 180 MPa to 230 MPa, the steady-state creep rate increased slightly but not significantly

(3) The creep experiment of the alloy was carried out at 980°C. Due to the higher temperature, the diffusion of atoms in this alloy became faster. Deformation was not only caused by the slippage of dislocations in the crystal but also by the diffusion of atoms. Therefore, the creep mechanism of single crystal alloy IC6SX at this temperature is a mixed mechanism of dislocation glide and diffusion

Data Availability

The research data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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