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Microstructure evolution and creep behavior of a [111] oriented single crystal nickel-based superalloy during tensile creep

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ABSTRACT

By means of creep curve measurements and microstructure observation, the microstructure evolution and creep properties of [001] and [111] oriented single crystal nickel-based superalloys are investigated. Results show that, after full heat treatment, the microstructure of both the oriented single crystal nickel-based superalloys consist of the cuboidal γ' phase embedded coherently in the γ matrix phase, and arranged regularly along the $<100>$ direction. During tensile creep, the cuboidal γ' phase in the [001] oriented superalloy is transformed into the rafted structure along the direction vertical to the stress axis, while rafting orientation of the γ' phase in the [111] oriented alloy is at an angle of about 40°–60° relative to the stress axis. During steady-state creep, the deformation mechanism of the [001] oriented alloy is mainly dislocations being activated in γ matrix channels and climbing over the rafted γ' phase, while that of the [111] oriented alloy is dislocations slipping in γ matrix channels and shearing into the rafted γ' phase. As creep goes on, dislocations concentrate to form the subgrain structure in the [111] oriented alloy. From the study of this paper, the creep anisotropy, especially the microstructure-evolution anisotropy and its effect on creep properties of single crystal superalloys, are further specified, which are expected to provide useful data for the design and production of single crystal superalloys.

1. Introduction

Single crystal nickel-based superalloys have been widely used to produce blade parts of aero-engines and gas turbines as they significantly raise the operation temperature and efficiency due to their excellent mechanical properties in service [1], especially the creep resistance. However, their inherent crystallography characters determine the anisotropy of their creep behavior.

All commercial single crystal superalloys are in the [001] orientation [2,3], which has attracted the interest of many researchers [4–9]. However, for actual engineering alloys, there inevitably exist misorientations deviating from the [001] orientation. Moreover, the structures of blade parts are complicated; for example, the cooling channels, which make the centrifugal force acting on different regions of working blades in service deviate from the [001] orientation to different extents. The misorientations have obvious effects on creep behavior of blade materials and relates to their life and security. Therefore, the study on the creep behavior of single crystal superalloys with orientations deviating from the [001] orientation is significant for the design and production of single crystal nickel-based superalloys [9].

The creep anisotropy of single crystal superalloys has been much studied from many aspects [11–19]. In literature [10], the creep resistance of the MAR-M200 SC superalloy oriented near $<001>$ and $<111>$ has been studied and found to be clearly better than that of the alloys oriented near the $<011>$ orientation in the temperature range 760–871 °C, while at 982 °C, the influence of crystal orientation on creep life becomes weaker. In literature [12], MacKay and Maier show that the single crystal nickel-based superalloy MAR-M247 oriented near the $<001>/<011>$ boundary in the stereograph triangle has relatively longer life than that oriented near the $<001>/<1\bar{1}1>$ boundary when being crept at 774 °C. Moreover, the stress rupture life of the alloy was strongly influenced by the crystal-rotation levels required in the creep specimens to produce conditions favorable for multiple slip, which is in good agreement with results in literature [13]. Literature [14] has made a more detailed study on the creep anisotropy of a single crystal superalloy when being crept at 975 °C/255 MPa, indicating that the creep-rupture properties are functions of the deviation degrees from the [001] orientation, and that the creep-rupture lifetimes of the specimens

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are not sensitive to the misorientation until the deviation degree exceeds about 30°.

As for the study on the anisotropy of single crystal superalloys, the work of U. Glatzel and his coworkers must be noted. In literature [15–19], the anisotropy creep behavior of <001>, <011> and <111> oriented superalloys were investigated, but most of which focus on the configuration and slipping behavior of dislocations, and do not involve the microstructure evolution of the alloys during creep. The microstructure evolution for different-orientation single crystal superalloys during creep was studied in literature [19], but it is limited and only gives the width of γ'/γ phases, and the morphologies of γ'/γ phases, especially the effect of the configuration evolution of γ' phase on the creep behavior of single crystal superalloys are not clarified.

In fact, the creep behavior of single crystal nickel-based superalloys has a close relationship with their microstructure evolution, which is also anisotropic. In recent years, some investigations have been carried out on the microstructure evolution of [001] and [011] oriented single crystal superalloys with the aid of microstructure observation and finite element analysis [20,21]. However, the microstructure evolution of [111] oriented single crystal nickel-based superalloys during creep is more complicated, which has an important effect on creep properties of the alloys, the study of which is significant for thorough comprehension of creep anisotropy for single crystal superalloys.

Thereby, in this paper, by means of creep curve measurements, the creep behavior of a [111] oriented single crystal nickel-based superalloy at high temperatures is investigated, combined with the microstructure observation by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The γ'-phase evolution and its effect on the creep behavior of the superalloys were emphatically studied. The creep behavior of the superalloy with [001] orientation is also studied to make a comparative analysis.

2. Experimental procedure

A single crystal nickel-based superalloy with [111] orientation was produced by means of the seed crystal method in a directional solidification vacuum furnace under a high temperature gradient. Misorientations in three-dimensional (3D) orientations of the alloy are determined by the Laue-back reflection method to be 19°, 4° and 17°, deviating from [133], [111] and [112] orientations, respectively. The chemical composition of the superalloy is listed in Table 1. The heat treatment regimes of the alloy are given as follows: 1250 °C, 4 h, AC and 870 °C, 32 h, AC.

In order to compare the effect of crystal orientations on the creep behavior of single crystal nickel-based superalloys, the [001] oriented single crystal nickel-based superalloy was also prepared by means of selecting crystal method, and the chemical composition of the alloy and the heat treatment regimes are the same as those of the [111] oriented alloy.

After full heat treatment, the bar of the [111] oriented single crystal superalloy was cut into the plate-like creep specimen along the $(\bar{1}01)$ and $(1\bar{2}1)$ crystal planes, and the [001] oriented superalloy was cut along the (100) and (010) crystal planes. The cross-sectional dimension of the specimens is 4.5 mm × 2.5 mm, the gauge length is 15.0 mm, and the schematic diagram of the creep samples is shown in Fig. 1. Tensile tests were performed in a GWT504-model creep testing machine under constant uniaxial loads of 137–180 MPa at 1040–1080 °C to measure creep curves, and the stress axis of the specimens is along [111] and [001] orientations for the [111] and [001] oriented superalloys, respectively. Microstructure and deformation features of the alloys at different states were observed by using SEM and TEM.

Table 1
Chemical composition of the [111] oriented single crystal nickel-based superalloy (mass fraction, %).

Cr	W	Al	Co	Ti	Fe	S	C	Ni
9.0	5.0	5.5	4.5	1.7	0.3	0.001	0.005	Bal.

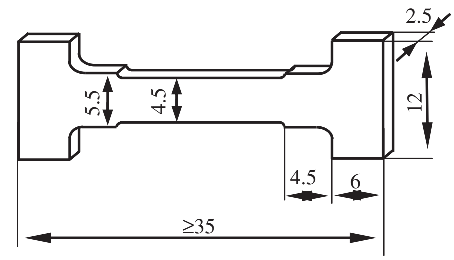

Fig. 1. Schematic diagram of the tensile creep samples.

3. Experimental results and analysis

3.1. Creep features of the alloys

The creep curves of the [111] oriented single crystal nickel-based superalloy under different conditions have been measured, as shown in Fig. 2. The creep curves of the alloy under the applied stress of 137 MPa at different temperatures are shown in Fig. 2(a), indicating that the alloy, when being crept at 1040 °C, displays a shorter primary creep stage, a lower steady-state strain rate and the longest creep lifetime. The strain rate of the alloy during steady state creep is measured to be 0.02129%/h, the last time of the alloy during steady state creep is about 93 h, and the strain of the alloy after being crept for 100 h is measured to be only 3.33%. Furthermore, the strain rate of the alloy increases gradually up to fracture once the creep enters the third stage, and the creep life of the alloy is measured to be 134 h. With the temperature elevated to 1070 °C, the strain rate of the alloy during steady state creep increases to 0.06131%/h, the last time of the alloy during steady state creep is shortened, and the creep lifetime decreases to 65 h, correspondingly. With the temperature further elevated to 1080 °C, the creep lifetime of the alloy decreases to only 45 h.

The creep curves of the [111] oriented alloy under different applied stresses at 1040 °C are shown in Fig. 2(b). The strain rate of the alloy during steady state creep increases slightly to become 0.05636%/h when the applied stress is enhanced from 137 to 160 MPa, and the creep lifetime of the alloy decreases to 73.5 h. When the applied stress further increases to 180 MPa, the creep lifetime of the alloy decreases to only 40 h.

Fig. 3 shows the creep curves of the [001] and [111] oriented superalloys under the conditions of 1040 °C and 160 MPa. Fig. 3(a) shows the relationship between the strain and time, indicating that the two alloys have different strain features when being crept up to fracture. The creep life of the [111] oriented alloy is about 74 h, far shorter than the 261 h of the [001] oriented superalloy. Fig. 3(b) shows the relationship between the strain rate and strain, indicating that for the two alloys, the strain rate has a similar changing trend, and almost equal minimum value. Before the strains reach 1.5%, the stain rate of the [111] oriented alloy has bigger decrease extent than the [001] oriented one, and after the strains exceed 8%, the [111] oriented one has bigger increase extent in strain rate.