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# Microstructure evolution and its effect on creep behavior of single crystal Ni-based superalloys with various orientations

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ABSTRACT

By means of microstructure observation, internal friction stress (IFS) and creep property measurements, the microstructure evolution and its effect on creep behavior of the [001]-, [011]-, and [111]-oriented single crystal Ni-based superalloys are investigated. Results show that the IFSes of the alloys with various orientations during steady-state creep decrease in turn according to the sequence of $\sigma_{i[001]}$, $\sigma_{i[111]}$ and $\sigma_{i[011]}$, which results in the creep lifetimes of the alloys at 1040 °C/137 MPa being the [001]-oriented alloy > the [111]-oriented alloy > the [011]-oriented alloy. It is determined according to the Schmid factors that the activated slipping systems in the [001]-, [011]- and [111]-oriented alloys during creep are 8, 4 and 6, respecrively. After crept for 50 h at 1040 °C/137 MPa, the γ′ phase in the [001]-oriented alloy is transformed into the N-type rafted structure, the bigger IFS and better creep resistance of the alloy is attributed to the superimposing action of the strain hardening and N-type rafted γ′ phase for hindering dislocations motions. During creep, the γ′ phase in the [011]-oriented alloy is transformed into the stripe-like rafts along [001] direction, the $\gamma_{r(010)}$ roof and $\gamma_{g(100)}$ gable channels retained in the one result in a weaker effect on hindering the slipping of dislocations. The lower IFS and weaker creep resistance of the alloy are attributed to the superimposing effect of little strain hardening and stripe-like γ′ rafted structure. During creep, the γ′ phase in the [111]-oriented alloy is transformed into the mesh-like rafted structure along (010) plane, and a few activated slipping systems cause only weaker strain hardening effect, which has little effect on hindering the dislocations movement. But the smaller Schmid factors of slipping systems provides only weaker driving force to promote the slipping of the dislocations. The combined action of the two aspects results in the IFS and creep strength of the [111]-oriented alloy located in between the [001]- and [011]-oriented alloys.



## 1. Introduction

Single crystal (SC) Ni-based superalloys have been widely used to produce blade parts of aero-engines and gas turbines due to their excellent mechanical properties and creep resistance at high temperatures, which may enhance the operation temperature and work efficiency of aero-engines [1]. Although all commercial SC superalloys are used in [001] orientation [2–3], the used alloys in engineering exist actually misorientations deviating from [001] orientation. Moreover, the structures of blade parts are complicated, for example, the cooling channels, which makes the centrifugal force acting on different regions of working blades in service deviating from the [001] orientation to different extents. Moreover, the misorientations have obvious effects on creep behavior and their life of blade materials. Therefore, it is significant to investigate the creep behavior of $<001>$-, $<011>$- and $<111>$-oriented SC alloys [4].

The investigation on the creep behavior of SC superalloy MAR-M200 with various orientations in the temperature range of 760–871 °C indicates that the alloys close to [001] and [111] orientations have better creep strength than that close to [011] orientation, and the [111]-oriented alloy at 872 and 982 °C has the longest creep life [5]. The study on the creep behavior of the alloy CMSX-2 with various orientations at 760 °C/750 MPa shows that the alloy with [001] orientation has the longest creep life, while the one with [111] orientation has the shortest one [6]. The creep life of the alloy SRR99 with various orientations at 760 °C decreases in turn according to the sequence of [001] > [111] > [011], while the sequence of the creep life of the alloys at 1040 °C becomes [111] > [001] > [011] [7], which is similar to the results in Ref. [8].

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However, the creep life of the various-oriented CMSX-4 alloy at 850 °C decreases in turn according to the sequence of [001] > [011] > [111] orientations [9,10], and it is thought that the quantity of γ channels and their orientations relative to the stress axis have important effects on creep behavior of the alloys. During steady-state creep, the SC alloy LEK 94 with precise [011] orientation has smaller strain rate than the one with precise [001] orientation, but the creep strength of the alloy deviating 10° from [011] orientation decreases sharply at 1020 °C/160 MPa [11].

Although the creep anisotropy of SC Ni-based superalloys has been studied [5–15], there seems to be no rule governing the anisotropy behavior of alloys with various orientations. For example, under similar creep conditions of intermediate temperatures and high stresses, the alloys CMSX-2 and CMSX-4 with <111> orientation have the worst creep strength [6,9–10], while the alloys MAR-M200 and SRR99 with <011> orientation have the worst creep strength [5,7], and the dependence of the creep anisotropy of alloys with various orientations on deformation mechanism is still not clear.

On the one hand, the various creep resistances of the alloys are related to their chemical compositions, such as the alloys with various compositions display the different effect of solution strengthening, and on the other hand, the creep behavior of alloys is related to their microstructure. Because the grain boundaries have been eliminated in SC Ni-based alloys, the strain of the alloys during creep originates only from the quantity and mobility of activated dislocations, which is related to the creep resistance of alloys. Moreover, it is thought that the creep resistance of SC alloys has close relationship with the internal friction stress (IFS, $\sigma_i$) of dislocation movements during steady-state creep. Here, the IFS is defined as the resistance that dislocation movement must overcome during creep, including the interaction of the stress fields in between neighboring dislocation lines and other obstacles of dislocations movement. Although the effect of the IFSes on the creep behavior of some SC alloys has been studied [16–19], which focus only on <001>-oriented alloys, the dependence of the creep anisotropy of SC alloys with various orientations on IFSes is unclear.

In this paper, by means of measuring the creep properties and IFSes, combined with microstructure observations, the creep behavior of the [001]-, [011]-, and [111]-oriented SC Ni-based superalloys was investigated, which may enrich the creep anisotropy theory of SC superalloys and provide the theory basis for the application of SC Ni-based superalloys.

## 2. Experimental procedure

The [001]-, [011]- and [111]-oriented SC Ni-based superalloys were produced by means of the selecting and seeding crystal methods in a directional solidification vacuum furnace under a high- temperature gradient. The nominal chemical composition of the alloys is Ni-9.0Cr-4.5Co-1.7Ti-5.0W-5.5Al (wt%). The heat treatment of the alloys is conducted in air and the regime is given as follows: 1250 °C × 4 h, A.C. + 870 °C × 32 h, A.C. By means of Laue-back reflection method, the misorientation of the [001]-oriented alloy is measured to be 7°, 26° and 22° deviating from [001], [113] and [012] orientations, that of the [011]-oriented alloy is measured to be 4°, 14° and 13° deviating from [011], [012] and [133] orientations, and that of the [111]-oriented alloy is measured to be 4°, 19° and 17° deviating from [111], [133] and [112] orientations. The misfit of the γ′/γ phases in the alloys at 1040 °C is measured to be $\delta = -0.34\%$ according to $\delta = 2(\alpha_{\gamma'} - \alpha_\gamma)/(\alpha_{\gamma'} + \alpha_\gamma)$ [20], where $\alpha_{\gamma'}$ and $\alpha_\gamma$ are lattice parameters of γ′ and γ phases, respectively.

After full heat treatment, the bars of the alloys with various orientations were cut into the plate-like creep specimens with the cross-section of 4.5 mm × 2.5 mm, and the gauge length of 20 mm. The wider plane of the creep specimens of the [001]-, [011]- and [111]-oriented alloys are cut along the (100), (100) and ($\bar{1}$01) planes respectively. The uniaxial constant load tensile tests were performed in a creep testing machine (GWT504 model) at 1040 °C/137 MPa, along [001], [011] and [111] orientations, respectively, to plot the creep curves. The IFSes of the alloys during steady-state creep under conditions around 1040 °C/137 MPa were measured by means of the method of strain transient dip tests [21,22].

The creep testing are stopped after being crept to steady-state stage and fracture at 1040 °C/137 MPa, and the specimens were polished into the films of about 60 μm in thickness, then the TEM specimens were prepared by twin-jet electro-polishing method. The microstructure and dislocation configurations of the alloys are observed under transmission electron microscope (TEM) to analyze the deformation mechanism of the alloys during creep. All TEM observations were made in the microscopy with TECNAI-G20 model.

## 3. Experimental results and analysis

### 3.1. Internal friction stresses and creep features of alloys

By means of the strain transient dip tests, the IFSes of the

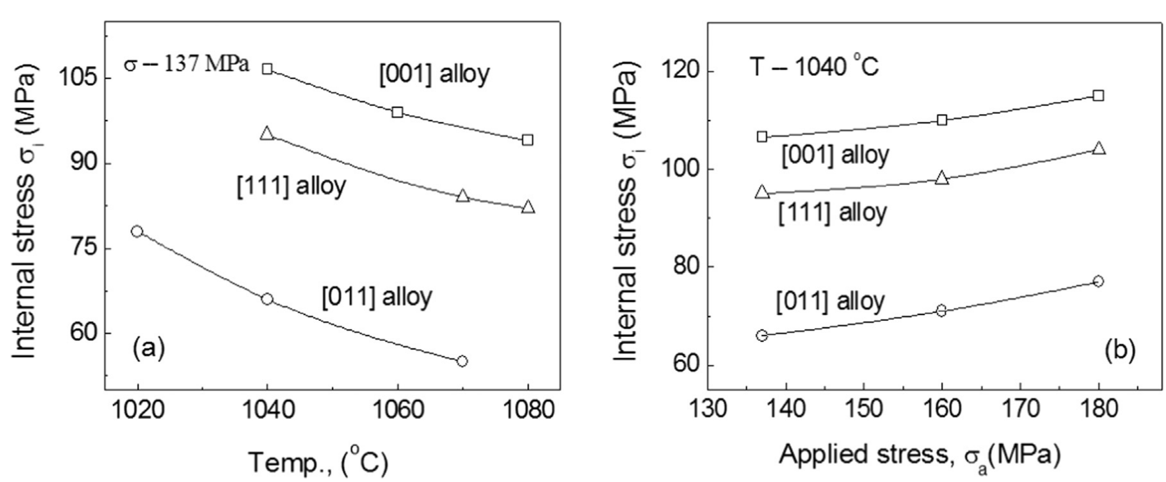


**Fig. 1.** IFSes of the [001]-, [011]- and [111]-oriented alloys during steady-stage creep under different conditions. (a) applied stress of 137 MPa at various temperatures, (b) applied various stresses at 1040 °C.