Rare Metal Materials and Engineering
Volume.50, Issue.4, April 2021
Available online at **www.rmme.ac.cn**

Science Press

Cite this article as: Du Yunling,Tan Zihao,Yang Yanhong,et al.Influence of Small Degree Deviation from [001] Orientation on Creep Behavior of Ni-based Single Crystal Superalloys[J].Rare Metal Materials and Engineering,2021,50(04):1132-1138.

Influence of Small Degree Deviation from [001] Orientation on Creep Behavior of Ni-based Single Crystal Superalloys

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Abstract: The creep behavior of Ni-based single crystal superalloys with small degree deviation from [001] orientation is strongly influenced by temperature, γ' phase size and the level of applied stress. This research presented a review on effects of small orientation deviation on creep behavior of single crystal superalloys. The variations in the creep properties of alloys with small degree deviation from [001] orientation originate from different deformation mechanisms. Besides, these mechanisms correspond to different threshold stresses which are associated with the occurrence of primary creep and creep rate. At intermediate temperatures (760~850 °C), the creep behavior of single crystal alloys is highly sensitive to small misorientation but relatively insensitive above 850 °C. The size of γ' phase is inferred to exert influence on the creep behavior of alloys with orientation deviation at intermediate temperatures. However, at elevated temperatures, the rafting process can be accelerated by higher thermal activation, and thus the mechanical properties become less relevant to the size of γ' precipitates.

Key words: single crystal superalloy; misorientation; creep behavior

Ni-based single crystal superalloys have been widely used in modern aircraft, especially high pressure turbine blades, considering their excellent creep resistance and tensile strength under elevated temperatures[1-10]. Creep property [11-16] is believed as an important part of the load spectrum of single-crystal Ni-based superalloys, which limits the service life of blades [17, 18]. Creep damage caused by the superposition of thermal stress and centrifugal stress is the main failure mechanism of advanced aircraft and gas turbine blades. Dye et al [19] found that a variation in CMSX-4 single crystal superalloy with 20° misorientation from [001] causes a variation in the creep strain at 20×10^6 s (about 5500 h), which can be attributed to off-axis orientations and cooling holes. Off-axis orientations experience higher thermal and centrifugal stresses in the web and correspondingly greater primary creep strains in the cooler web locations [19]. The distribution of thermal and centrifugal stresses in turbine blades is shown in Fig.1. During the service of single crystal superalloy turbine blade, elastic anisotropy leads to orientation-dependence thermal distribution, as shown in Fig.1a. The stresses after application of the thermal and centrifugal loads dominate the response during the initial stages of service (Fig.1b). The load shifts from the primary creep to the tertiary creep, after about 5500 h of creep (Fig.1c), and the variation of stress distribution across the blade section is much smaller.

In service, the Ni-based single crystal superalloys possess superior creep resistance but demonstrate a strong anisotropy of mechanical properties. Therefore, the creep anisotropy of alloy has attracted increasing attentions [20, 21].

In generally, Ni-based single-crystal superalloys are fabricated along [001] orientation due to their excellent comprehensive properties and preferred growth direction (Fig.2). Nevertheless, a certain deviation from [001] orientation is definitely considered to exist in single crystal alloys. However, the work

Received date: April 17, 2020
Foundation item: National Science and Technology Major Project (2017-VI−0003-0073); National Key R&D Program of China (2017YFA0700704); National Natural Science Foundation of China (51701210, 51601192, 51671188); Youth Innovation Promotion Association, Chinese Academy of Sciences
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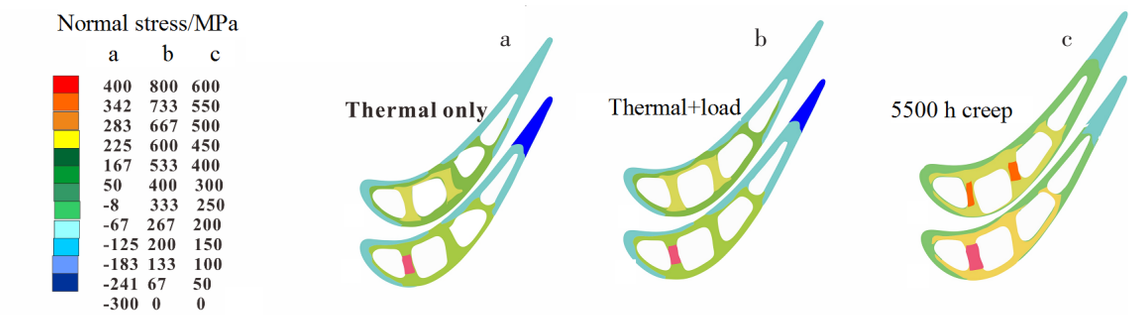

Fig.1 Normal stress distribution in the turbine blade section: (a) thermal distribution, (b) intial stages of life, and (c) thertiary creep [19]

about the influence of small deviation from [001] orientation on creep behavior of Ni-based single crystal superalloys is rare. Previous studies about creep anisotropy of single crystal superalloys were mainly focused on [001], [011] and [111] orientations. Therefore, the research progress of creep anisotropy with small angle deviation from [001] orientations was thoroughly introduced in the present work. Previous researches illustrated that the anisotropic creep is strongly dependent on orientation, temperature, γ' phase size and the level of applied stress [22-24]. This research is to elaborate the research progress of the misorientation dependence of creep behavior of single crystal superalloys by following aspects.

(1) Single crystal alloys with small deviation within 20° from [001] orientations exhibit better creep properties when they are closer to the [001]-[011] boundary compared to the [001]-[111].

(2) The temperature dependence on creep properties of single crystal alloys with small orientation deviation is rooted in the variation in the creep deformation mechanisms. The primary creep behavior of single crystal superalloys is considerably sensitive to small misorientation at about 800 °C but insensitive above 850 °C.

(3) The mechanical properties of Ni-based single crystal superalloys are enhanced by precipitation strengthening and solid solution strengthening effects. And their deformation mechanism can be affected by different stresses. The threshold of stress is associated with the occurrence of primary creep, the creep rate, the nucleation and propagation of dislocation.

(4) At intermediate temperatures, the size of γ' precipitates is considered to influence the creep property of single crystal superalloys with small orientation deviation. At elevated temperatures, however, no significant changes are expected in the creep performance of alloys with different γ' phase sizes.

1 Creep Behavior of Single Crystal Superalloys Deviated from [001] Orientation

Single-crystal nickel alloys are inherently anisotropic [25-27], while the preferred growth direction is considered as [001] orientation which is favorable to creep resistance and fatigue properties. Moreover, the creep performance is not only controlled by the angle deviating from [001] orientation, but influenced by the direction of misorientation.

Mackay et al [28] studied the influence of orientation on the rupture life of MAR-M247 single crystal alloy at 724 MPa and 774 °C (Fig.3). The primary creep strain was found to be

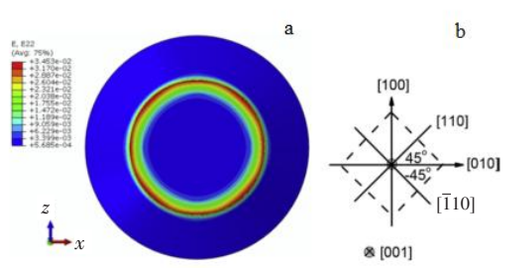

Fig.2 Axial strain distribution at the secondary creep stage for [001] orientation (a) and analysis of crystal orientation (b)[20]

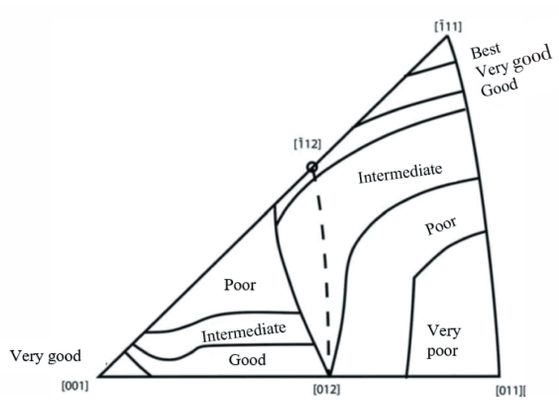

Fig.3 Orientation dependence of creep performance as described by Mackay and Maier [28]

greatly influenced by intersecting slip produced by lattice rotation. Ni-based single crystal superalloys with orientations within 25° from the [001] exhibited better creep properties when they are closer to the [001]-[011] symmetry boundary rather than [001]-[111] boundary. During creep deformation, smaller crystal rotations are required when the misorientation direction is closer to the [001]-[011] boundary which can be rationalized by the easier activation of cross-slipping as well as second stage creep. However, the launch of cross-slipping is relatively hard in the single crystal alloys with direction adjacent to [001]-[111] boundary, thus bringing about a larger creep strain. Rae et al[29] studied the effect of orientation on the primary-creep mechanism of the single-crystal alloy CMSX-4 with orientations within 20° from the [001] axis under the condition of 750 °C and 750 MPa. The results showed that the closer the tensile axis approaches the [001]-[011] symmetry boundary, the lower the primary creep strain of the alloy, which is similar to MAR-M247 alloy.

2 Different Factors

2.1 Effect of temperatures

The creep properties of single crystal alloys with small orientation deviation are believed to be highly influenced by the service temperature, which is rooted in the different creep deformation mechanisms under different conditions. The initiation of creep deformation in single crystal alloys is the movement of matrix dislocation.

The primary creep behavior of alloys with [001] orientation is considerably sensitive to small misorientation at approximately 800 °C but insensitive when the temperature exceeds 850 °C. Under the condition of 750~850 °C and 500 MPa or higher, the dislocation movement is restricted in γ channels while the $a/2<110>\{111\}$ dislocations form, indicating the initiation of creep deformation. $a<112>$ ribbons are nucleated from $a/2<110>\{111\}$ dislocations in the γ matrix by stress.

In the seminal research[28], the dislocation ribbons with overall Burgers vector $a<112>$ can cut through the γ' phase without leaving dislocation debris at the γ/γ' interfaces which are considered as the deformation mechanism of single crystal alloys under low-temperatures (in the vicinity of 750 °C) and high-stress regime (400~800 MPa). In the γ matrix along with the expected $a/2<110>$ dislocations, dislocations with overall Burgers vector $a<112>$ are able to decompose into superlattice partial dislocations separated by intrinsic and extrinsic stacking faults. The onset of primary creep deformation is associated with $a/2<110>$ dislocation progressively filling the horizontal γ matrix and the propagation of $a<112>$ dislocation ribbons which can cut through both γ and γ' phases[30]. Note that the nucleation of $a<112>$ dislocation ribbons from the $a/2<110>$ dislocation is insufficient to ensure the continuous primary creep deformation. Moreover, a stacking fault shearing originated from the propagation of $a<112>$ dislocation ribbons is required before the γ channels become clogged with $a/2<110>$ dislocations [30]. When the primary creep initiates under the condition of above 950 °C and 185 MPa or less, the movement of $<110>\{111\}$ dislocations is considered to be the dominate deformation mechanism. At elevated temperatures, $a/2<110>\{111\}$ dislocations form and propagate in the γ matrix. With the progress of creep deformation (the end of the prime of creep), the dislocation in the γ matrix increases rapidly and begins to accumulate at the γ/γ' interface (Fig.4). The accumulated interfacial dislocation networks can effectively prevent dislocations from cutting from γ matrix into γ' precipitate[31, 32]. Hence, the creep behavior of single crystal alloys becomes less dependent on the variation of orientation deviation at elevated temperatures. Matan et al[22] has carried out creep strain tests for various specimens of CMSX-4 superalloy single crystals which are deviated by up to 20° from [001] systematically. Creep deformation is controlled by $<112>\{111\}$ at 750 °C but it changes to $<110>\{111\}$ at 950 °C, as observed by transmission electron microscopy (TEM). Wang et al[33] study showed that the small deviation from [001] orientation contributes to different creep behavior in single crystal alloys, which is due to the various dominant deformation mechanisms. Nevertheless, the influence of small deviation from [001] orientation on creep behavior of single crystal superalloys is weakened by the rafting of γ' precipitate at high temperatures.

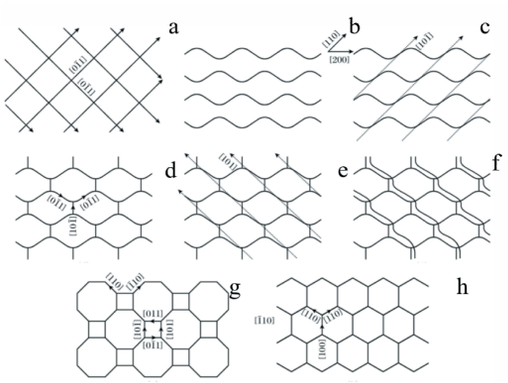

Fig.4 Formation mechanism of dislocation networks at the γ/γ' interface: (a) initial formation, (b, c) accumulation of dislolation networks, (d, e, f) reorganization of dislocation networks, and (g, h) stable disolation networks[31]

2.2 Effects of stress

Ni-based single crystal superalloys are considered to be provided with precipitation strengthening and solid solution strengthening, and their creep deformation mechanism can be affected by different stresses. Therefore, different deformation mechanisms correspond to different threshold stresses.

Previous studies[34,35] have shown that the deformation mechanism of the alloy is controlled by the dislocation by-passing the γ' phase through the climbing mechanism under low stress (Fig. 5). In the medium stress region, the dislocation can cut into the γ' phase and dissociate into superlattice partials separated by the intrinsic or extrinsic stacking faults, while under the high stress conditions, the dislocation shearing into the γ' phase becomes the main deformation mechanism. Pollock et al[36] reported that dislocation climbing can occur under low stress condition, and dislocation shearing into γ' phase is the main creep de-

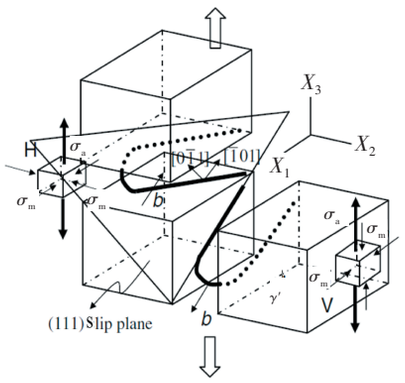

Fig.5 Sketch of dislocation lines showing slip through the γ channels on the (111)<101>system (small cubes depict state of stress in the γ channels, comprised of compressive in-plane misfit stresses (σ_m) and the applied stress (σ_a); γ phase is relaxed only when dislocations can slip in both channels, and thus the required applied stress for yielding of γ is controlled by the RSS in the vertical channel) [34]

formation mechanism under high stress condition. The creep properties of alloys with different misorientation from [001] direction are highly dependent on the applied stress. The creep rate, the nucleation and propagation of dislocation start when the critical stress is reached. Pollock and Argon[24] studied the creep deformation behavior of CMSX-3 at 825 °C and 450 MPa. The dislocations propagated from grown-in dislocation looping through the narrow γ matrix channels, which is not considered as stacking fault shearing. In this work, it is likely that there is no sufficient stress for these dislocations to cut into the γ' phase. Rae et al[30] elucidated factors of primary creep when the tensile stress is orientated within 20° from [001] directions (in CMSX-4). In the range 750~850 °C, the primary creep occurs when threshold stress exceeds 500 MPa; thereafter, the accumulation of primary creep strain is proportional to the magnitude over the threshold stress. If the applied stress is sufficient, the a<112> dislocation ribbons are produced by the a/2<110> {111} dislocation, which is generated in γ matrix; a typical reaction may occur[22]:

$$a/2[011] + a/2[101] \rightarrow a/3[112] + a/6[112] \quad (1)$$

In Fig. 6a, the a/3[112] dislocation is able to enter the γ' phase, leaving a superlattice intrinsic stacking fault (SISF) and a/6 [112] at the γ/γ' interface. In Fig. 6b, the original a/6[112] and a further a/6[112] enter the γ' phase, thus leaving an a/3 [112] partial dislocation at the interface [30].

The creep life of DD6 single crystal superalloy was previously reported by Wen et al[20], as shown in Table 1. The above experimental results might be associated with the stress redistribution which was aniseed from the notched stress concentration. At the beginning of creep, the creep strains are mainly produced in the notched region which is subjected to the multiaxial stress state. As secondary or further slip systems become activated, the creep rate decreases during the primary creep deformation process [37].

Han et al [38] studied the effect of threshold stress on creep properties of single crystal superalloy SRR99 at 760 °C, as shown in Fig. 7. The creep properties of SRR99 single crystal with different misorientation degrees from [001] direction are dependent on dislocation shearing of γ' precipitates. Stacking faults are occasionally found in local areas of γ' particles. However, creep deformation is deemed to be dominated by <110>{111} and <112>{111} slip systems under the threshold stress condition. The <112>{111} slipping was referred to "stacking fault shearing", which was used to describe the movement of the dislocation ribbons by Rae and Reed [30, 39]. In a series of papers, stacking fault shearing was observed at 850 °C and 650 MPa, while <112>{111} slipping was absent when the stress reduced to 500 MPa. It is indicated that there is a stress threshold for the occurrence of stacking fault shearing [40]. No stacking-fault shearing in <112> {111} was observed via the transmission electron microscope [23]. It is argued that the smaller primary creep approaches the [001]-[011] symmetry boundary, which is not the interaction between two equal-stress <112> {111} systems, but the lack of either. The above inference reveals that the hardening process is more complex than the simple picture of Ref.[28].

2.3 Effects of γ'-particle size

The creep properties of Ni-based single crystal superalloys with small misorientation from [001] orientation is affected not only by temperature and stress, but also by the size of gamma precipitation. Caron et al [41] studied the creep deformation behavior of CMSX-2 at 760 °C and 750 MPa. In the paper, γ' sizes of 0.23, 0.3, and 0.45 μm were obtained through three different aging heat treatments (Fig.8).

In the γ' sizes of 0.45 μm, the deformation is operated by homogeneous <110>{111} multiple slip in the matrix, leading to the formation of dense dislocation networks at the γ/γ' interfaces rapidly. The dense dislocation networks can inhibit dislocation shearing into γ' phase. When the size of γ' phase decreases to 0.23 μm, the creep deformation mechanism is dominated by <112> dislocation shearing the γ/γ' interfaces and 1/3<112> dislocation with the superlattice partial dislocation separated by intrinsic and extrinsic stacking faults with cut into the γ' phase. At intermediate temperatures, the size of γ' precipitates is considered to influence the creep property of single crystal superalloys with

Table 1 Experimental results of DD6 notched specimens [20]

Specimen	Orientation	Misorientation	Life time/h	Rupture strain/%	Elongation/%	Reduction of area/%
1	001	2.3	198.1	0.82	0.65	1.9
2	001	3.1	208.9	1.5	0.74	1.7
3	001	1.7	205.6	1.2	0.71	1.7

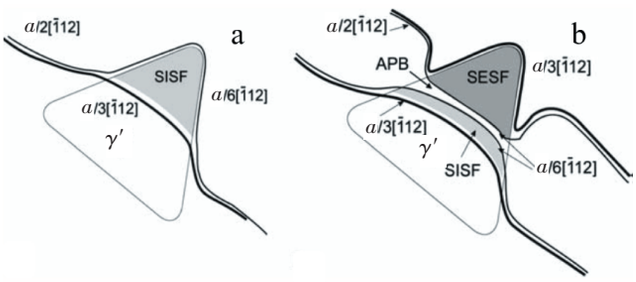

Fig.6 Illustration of mechanism of shearing of the γ' by an a<112> ribbon during primary creep: (a) $a/3[\bar{1}12]$ dislocation entering γ' and (b) $a/3[\bar{1}12]$ dislocation at interface[30]

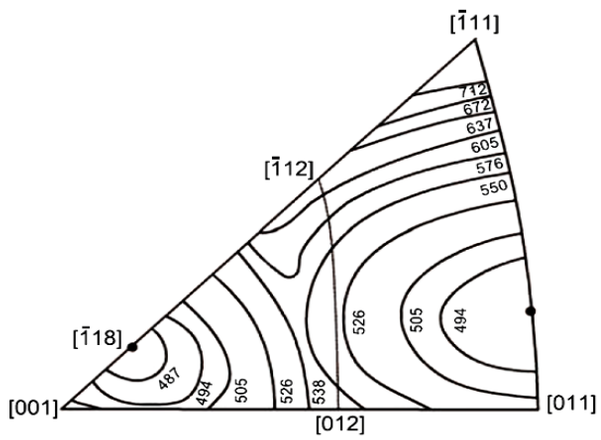

Fig.7 Distribution of applied stress (MPa) exerted on single crystals to activate γ'-shearing mechanism by partial dislocations[38]

small orientation deviation. At elevated temperatures, however, no significant changes are expected in the creep performance of alloys with different phase sizes.

During the high temperature creep deformation, the γ' phase becomes rapidly rafted (Fig.9). Orowan stress decreases while the width of the matrix channels increases after γ' rafting[43]. Thus it can become easier for dislocation movement. Thus, the dislocation movement becomes easier in the matrix which resists dislocation shearing into γ'.

3 Future Research

The creep behavior, which is considered as the most important indicator to measure the temperature capability of Ni-based single crystal superalloys, has been widely studied. The research progress of influence of small orientation deviation on creep properties is discussed in this work. Nevertheless, in the actual deformation process, the mechanisms are associated with each other. As the inlet temperature of engine turbine increases, the cooling channel of single crystal turbine blades becomes more and more complicated, so the blade wall thickness decreases significantly. The creep life is strongly affected by the change of blade wall thickness. Therefore, considering the research and application of the alloy, it is necessary to fur-

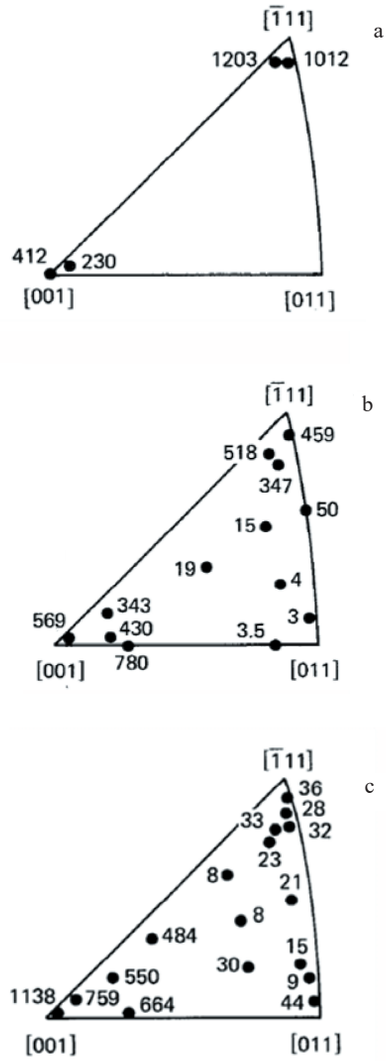

Fig.8 Orientation dependence of the stress rupture life (h) at 760 °C and 750 MPa of CMSX-2 single crystals with different γ' sizes: (a) 0.23 μm, (b) 0.3 μm, and (c) 0.45 μm[41]

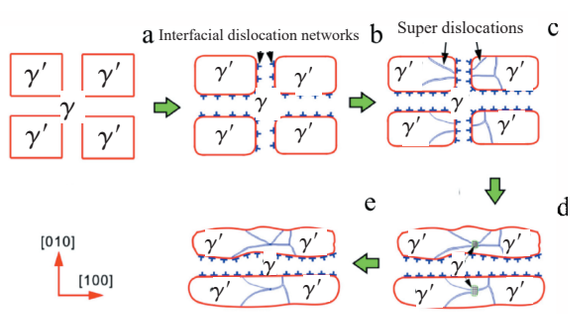

Fig.9 Schematic illustration of microstructure evolution during high temperature and low stress creep (dislocations in the γ' phase connect after the γ matrix vanishing): (a) after heat treatment; (b) primary stage; (c) initial steady stage; (d, e) later steady stage or after rupture[42]

ther study the influence of small degree deviation from [001] orientation on creep behavior in combination with the thickness of the specimen:

1) The effect of different deviated orientation and magnitudes of specimen thickness on creep behavior of superalloy should be established.

2) The relationship between the rafting of γ' phase and creep degradation of single crystal superalloys should be established under the condition of the same wall thickness at different deviation angles. Moreover, in order to explore the hindrance effect of the rafted γ' phase to creep deformation, the internal relationship between the degree of rafting and creep properties of the alloy is built by studying the thermodynamic and dynamic mechanisms of γ' rafting.

3) The effects of different types of dislocations on creep process have the necessity to be studied. The micro-interaction mechanism between dislocation, γ' phase and pore should be built under the condition of the different wall thicknesses at the same deviation angles, which will provide a theoretical basis for improving creep properties of alloys.

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镍基单晶高温合金的小角度偏离[001]取向对蠕变性能的影响

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摘　要：小角度偏离［001］取向的镍基单晶高温合金的蠕变性能受温度、γ'尺寸和应力条件的影响。本文综述了镍基单晶高温合金的［001］取向小角度偏离对蠕变性能的影响。不同程度的偏离引起的不同蠕变性能变化，源于不同的蠕变变形机制。不同的蠕变变形机制对应着引起蠕变发生的不同临界应力。在中温（760~850 °C），合金的蠕变性能对［001］取向的角度偏离很敏感，即使角度有轻微变化也会对蠕变性能有明显影响，但是温度高于850 °C时，小角度的取向偏离对蠕变性能影响不大。γ'尺寸对小角度偏离的合金蠕变性能的影响受温度制约。在中温，γ'尺寸的变化影响着小角度偏离引起的蠕变性能变化，但是在高温γ'相快速伐化，变形机制和γ'尺寸变化无关。

关键词：单晶合金；取向偏离；蠕变行为

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