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Anisotropy of high cycle fatigue behavior of a Ni-base single crystal superalloy

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ABSTRACT

The rotary bending high cycle fatigue properties of a single crystal superalloy in three orientations were tested at 700 °C in ambient atmosphere. The [011] orientation shows the highest fatigue strength. Moreover, the fatigue strength with ⟨111⟩ orientation is obviously higher than that with ⟨001⟩ orientation. There are two types of fracture modes, one is cleavage fracture for the [001] orientation, the other is the mixed fracture of cleavage and tearing for the [011] orientation. The ⟨011⟩ orientation shows more pronounced crystal lattice rotation than the ⟨111⟩ orientation. Nevertheless, lattice rotation does not occur in the crystals with [001] orientation. Fatigue steps of the [001] and [111] orientated crystals propagate along different {111} glide planes, which means that the slip in ⟨111⟩ orientation moves more easily than in ⟨011⟩ orientation. The typical deformation mode of [001], [011] or [111] orientation is respectively slip bands running through γ and γ' phases, dislocation pairs shearing γ' particles, or superlattice stacking faults besides high-density dislocation shearing γ' particles.

1. Introduction

Single crystal nickel-base superalloys, which are widely used for turbine blades of aircraft engines, show a strong anisotropy of mechanical behavior [1]. For example, the rupture life is longest for the ⟨111⟩ orientation, somewhat shorter for the ⟨001⟩ orientation and shortest for the ⟨011⟩ orientation when Mar-M247 and MAR-M200 single crystals were tested in the temperature range 760–774 °C [2]. Creep resistance of CMSX-4 alloy at 650 °C depends strongly on the crystal orientation, for creep in tension it decreases in the sequence ⟨111⟩, ⟨001⟩, ⟨011⟩ and for creep in compression it decreases in the sequence ⟨001⟩, ⟨111⟩, ⟨011⟩ [3]. Nevertheless, Caron et al. [4] found that the creep anisotropic behavior of nickel-base single crystal superalloys is extremely sensitive to the orientation and γ' precipitate size at intermediate temperatures. For CMSX-2 single crystals tested at 760 °C, the ⟨111⟩ orientation has considerably shorter creep lives than the ⟨001⟩ orientation [5]. At elevated temperatures the mechanical properties can range from excellent to poor depending on the orientation of the crystal with respect to the stress axis [6]. Early work by Winstone [7] on the first generation single crystal superalloy SRR99 has shown that the creep strength of [001] orientation is stronger than that of [111] at the lower temperature and this trend of anisotropy is reversed with increasing temperature. The {111}⟨112⟩ slip system is the characteristic slip system in the Ni-base superalloy single crystal at intermediate temperature [2,8,9]. Studies on the orientation dependence of the stress rupture properties of a single crystal superalloy SRR99 reveal that the stress rupture life ranks in the order [001] > [111] > [011] and the lattice rotation results from the dominant ⟨112⟩{111} slip system during the stress rupture test [10]. The yield strength of PWA1480 alloy with ⟨001⟩ orientation is different with ⟨011⟩ orientation, although both orientations have identical slip system during the deformation process [11]. Although many works have been investigated on the mechanical behavior for different orientations, there are many contradictory results concerning the mechanical properties of different orientations in previous investigations. Especially systematic work on anisotropy behavior of high cycle fatigue is still rather limited until now. Emphasis is laid on typical fatigue fracture behavior of SRR99 single crystal superalloy with [001], [011] and [111] orientations at 700 °C, where the effect of anisotropy is prominent. The fracture characteristics and mechanisms of different orientations have been systematically revealed.

2. Experiments

The material used in this study is a single crystal superalloy SRR99. It is a Ni–Al–Ti–Cr–W–Co–Ta alloy which was prepared by directional solidification along ⟨001⟩, ⟨011⟩ and ⟨111⟩

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orientations that was controlled by using a seed crystal. The single crystals were grown along ⟨001⟩, ⟨011⟩ and ⟨111⟩ orientations with deviation no larger than 6°, which had been tested by electron backscatter diffraction (EBSD). After casting into bars with a diameter of 15 mm and a length of about 220 mm, all specimens received a standard heat-treatment which was following: 1300 °C/4 h AC+1100 °C/4 h AC+870 °C/16 h AC (AC: air cooling). And then, cylindrical smooth test specimens with a diameter of 6.25 mm and a length of 52 mm were machined out along different orientations.

All the specimens were fatigue tested under load control at a stress ratio $R=\sigma_{min}/\sigma_{max}= -1$ at a frequency of 83.3 Hz. The tests were conducted at 700 °C. Rotating bending loading mode was adopted, as a result of which sinusoidal waveform was performed on the specimens. After ultrasonic cleanout, all the fracture surfaces were observed by a Cambridge S-360 scanning electron microscope (SEM).

3. Results and discussion

3.1. S–N curves

The relationship between the maximum applied stress amplitude (σ) and life to failure (N) for smooth specimens with ⟨001⟩, ⟨011⟩ and ⟨111⟩ orientations at 700 °C are shown in Fig. 1. Note that the arrows indicate that the specimens were not failure during tests. The general trend of the S–N curve is that the fatigue life increases with the maximum stress decreasing. Fatigue strength (limit) that is the threshold stress for crack propagation and not the critical stress for crack initiation is usually defined as the stress amplitude for a specimen not to fracture after 10^7 cycles. As can be seen from Fig. 1, the fatigue limits of specimens with [001], [011] and [111] orientations are 345 MPa, 385 MPa and 355 MPa, respectively. Therefore, the [011] orientation shows the highest fatigue strength, whose order is not in agreement with previous creep results [2–7]. It is noted that the fatigue data in [111] orientation fluctuated very much and sometimes fatigue properties in the [111] orientation is greater than that of specimens with ⟨011⟩ orientations at 700 °C. Due to stress ratio $R= -1$, not only tensile properties but also compressive properties have an important effect on HCF strength of a single crystal superalloy. Tensile and compression strength of specimens with [001], [011] and [111] orientations shown in Table 1 are the average value of three test specimens. From Table 1, it can be seen the [011] orientation displays the highest compression strength. It accords very well with the results in previous studies [12]. Though the fatigue limits are remarkably less than the compressive strengths of [001], [011] and [111] orientations, their variety trend is the same.

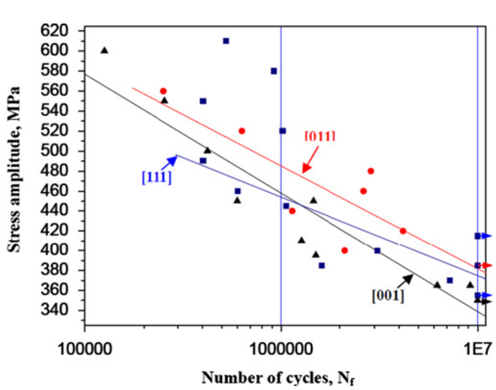

Fig. 1. *S–N* curves for SRR99 alloy with different orientations at 700 °C.

3.2. Fractograph

Fatigue crack initiation and crack growth are a consequence of cyclic slip in slip bands. It implies cyclic plastic deformation as a result of moving dislocations. Observations by SEM show that there are two types of fracture modes, one is cleavage fracture for the [001] orientation corresponding to $\sigma=365$ MPa, $N=9.18\times10^6$ cycles as shown in Fig. 2 (a) and (b); the other is the mixed fracture of cleavage and tearing for the [011] orientation corresponds to $\sigma=480$ MPa, $N=2.64\times10^6$ cycles as shown in Fig. 2(c) and (d). The fractographs of three orientations are composed of crack initiation stage, crack propagation stage and final rupture stage, as shown in Fig. 2(a), (c) and (e), respectively. It reveals that multiple crack initiation sites are observed at or near the surface due to rotary bending loading mode, which makes the surface of sample endure the maximum of pulsating stress. When fatigue cracks are initiated at the surface, surface condition (depth and orientation of surface irregularities), residual stresses and testing environment have a pronounced influence on the fatigue lifetime. Fatigue cracks start at the surface rather than at interior inclusions, whereas high compression stresses increase the limiting stress for surface crack initiation.

In the [001] single crystals, high temperatures and low strain rates result in wavy, homogeneous slip (stage II), whereas low temperatures and/or high strain rates often produce planar heterogeneous slip and crystallographic fatigue crack growth along {111} type of crystal planes (stage I). Failure in [001] orientations occurs in a fast and catastrophic manner, with multiply cracks growing along heterogeneous shear bands which lie along {111} type planes (Fig. 2(b)). One step forms within 1 cycle but 1 cycle unnecessarily induces the formation of one step. With the increase in the distance between two steps, the crack growth rate is increased within the crack propagation stage. Some secondary cracks are also observed in the crack propagation stage (Fig. 2(b)). The secondary crack paths show a favorable direction on the slip planes. In agreement with previous observations [13], the lattice rotation does not occur in SRR99 single crystal samples with [001] orientation as these orientations are stable due to the symmetry of the slip systems.

The observations from Fig. 2(c) and (d) show typical SEM images of fracture surface in ⟨011⟩ orientation at 700 °C. These also show a transition from stage II to stage I type of fracture in the [011] orientation, where cracks have been found to propagate in multiple {111} types of crystal planes. In general, the cleavage fracture with some ductile dimples is observed in the [011] orientations. It is interesting to note that the single crystals in ⟨011⟩ orientation show the bigger lattice rotations under the rotary bending fatigue at 700 °C, which is similar to the lattice rotation of aluminum and copper single crystals at cyclic loading with alternate tension and compression [14–16]. During plastic deformation at 700 °C, single crystals in ⟨011⟩ orientation rotate toward their slip direction. Under the condition of unidirectional tension, the axial direction of face-centered cubic single crystals rotated to the main glide direction. Under the condition of unidirectional compression, the axial direction of face-centered cubic single crystals rotates to the normal direction of the gliding plane.

For the crystal near [011] orientation, lattice rotation toward $[\bar{2}11]$ direction results from activity of the {111} $\langle 11\bar{2}\rangle$ or toward $[\bar{1}01]$ from activity of {111} $\langle 1\bar{1}0\rangle$ slip systems [17,18]. For the crystal near [111], the lattice rotates toward $[\bar{2}11]$ direction since the $[\bar{2}11]$ glide direction is the bisector of two elementary glide directions $[\bar{1}01]$ and $[\bar{1}10]$ [11]. During the cyclic loading process for that [001] orientation, several ⟨110⟩ {111} slip systems are activated so that lattice rotation does not occur.