Fracture analysis of a Ni-based single crystal superalloy

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Abstract. Based on the tensile stress-dominated low cycle fatigue (LCF) tests at 760°C, the fracture morphology of a second-generation Ni-based single crystal superalloy (SC) was studied in this paper. It was found that under LCF loading the specimen cracked with one fatigue source. The angle of fatigue bands in crack propagation region was related to the secondary orientation deviation from crystal orientation [100]. In addition, evidence showed that the specimens fractured along the slip surface of \{111\}\langle 110\rangle octahedral slip systems.

1. Introduction
Nickel based single crystal superalloy (SC) is used for most turbine blades in aircraft engines and land-based gas turbines\textsuperscript{[1]} nowadays due to the outstanding anti fatigue and creep function of it\textsuperscript{[2]}. In the serving time, turbine blades undergo cyclic loading, facing the risk of low cycle fatigue (LCF) fracture. Research on the fatigue property is of great significance.

Ni-based single crystal is a kind of face-centered cubic (FCC) material. For most commercial Ni-based single crystal superalloy blades in the world market, the axial direction is cast to [001] crystallographic orientation within 15° deviation, which is called the primary orientation; and the other two directions are in random\textsuperscript{[3]}, which is called secondary orientation.

2. Materials and Methods
In the work of this paper, a kind of Ni-based single crystal superalloy was studied. Tensile stress-Dominated LCF tests were carried out in a temperature of 760°C and stress ratio $R=\sigma_{\text{max}}/\sigma_{\text{min}}=0.1$. The dimension of the specimen is shown in Figure 1. The crystal orientation of loading direction is [001] and the width direction is [010] or with a certain deviation angle from [010]. Specimens with different secondary orientation were test in the same LCF condition. After a number of cycles, the specimens cracked into two parts. The fracture surface characteristics and subsurface $\gamma'$ precipitates of the specimens were studied.
3. Results & Discussion

The SEM results of the fracture surface are shown in Figure 2. The three specimens all have a primary orientation of $\alpha=3^\circ$ and the secondary orientation $\beta$ being $0^\circ$, $10^\circ$, $15^\circ$ respectively. The fracture area can be divided into three parts: fatigue source region, crack propagation region, and final instant rupture region. Single fatigue source can be seen in fatigue source region, which is relatively smooth. Crack propagation region is characterized by the parallel fatigue bands. At the final stage of fracture, cleavage step was formed in the final instant rupture region.

3.1. Fatigue source

At the fracture surface of each specimen, there is a circle which is called fatigue source, which means fatigue crack originates from this point of material. At the center of the circles, void defect can be seen, which indicates that the fatigue damage starts from the void defect in the material. When focusing on the position of the fatigue source, it can be concluded that all of them are located in one side and the subsurface of the specimen. These characteristics are similar to the fatigue tests of other metal except of the number of fatigue source. In other fatigue test of Ni-based single crystal superalloy, usually more than one fatigue source are found\cite{4} while on the fracture surface of this material only one fatigue source was found.

3.2. Crack propagation

In the central part of fracture surface is the crack propagation zone, covering most of the area. It is the region where the fatigue crack grown in a uniform speed, resulting neat fatigue bands, which is obvious in Figure 2 (a) and (b).
Figure 3 and Table 1 shows the secondary orientation and the fatigue bands direction of (a) and (b). The secondary orientation deviation from [100] of the two specimens is 1.4° and 10.7° respectively. The angle between the fatigue band and [100] orientation is 5° and 16° respectively. The difference of these two angles are 3.6° and 5.3° respectively, which may be the result of machining error. The fatigue bands angle increases with the increase of secondary orientation deviation. So the angle of fatigue band is dependent on the secondary orientation deviation angle from [100]. In these two cases, the direction perpendicular to the fatigue band is always consistent with [010], so it comes the conclusion that fatigue crack propagates along the orientation of [010].

![Figure 3. The secondary orientation and the fatigue bands direction](image)

| Specimen | Secondary orientation deviation $\beta/^{\circ}$ | Fatigue bands angle $\theta/^{\circ}$ | $(\theta-\beta)/^{\circ}$ |
|----------|-------------------|-------------------|-------------------|
| (a)      | 1.4               | 5                 | 3.6               |
| (b)      | 10.7              | 16                | 5.3               |

3.3. Final instant rupture

Final instant rupture region is macroscopically characterized by relatively rough fracture surfaces and is generally located opposite the fatigue source region\(^{[5]}\). Figure 4 is the fracture morphology of specimen (c) with the secondary orientation deviation from [100] being 15°. From the figure, it can be seen that there is a right triangle pyramid feature in the lower right corner. The angle between the hypotenuse of triangular pyramid and the edge of the specimen is measured to be $\varphi=34^{\circ}$. And $\beta$ is the secondary orientation deviation angle from [100], so $\beta=15^{\circ}$, and $\varphi+\beta=34^{\circ}+15^{\circ}=49^{\circ}$.

According to the damage theory of Ni-based single crystal superalloy, octahedral slip systems $\{111\}<110>$ are the possibly activating slip systems. By contrast, the inclined plane of triangular pyramid ABC is the $(111)$ crystal plane.
At the tip of the secondary crack, some lines parallel to the crack propagation direction can be seen, as shown in Figure 5. Most of that are concentrated in front of the crack tip, and others are distributed on both sides of the crack tip. The material is cut into strips by the lines without changing the shape and size of $\gamma'$ precipitate, but the patterns of $\gamma'$ precipitate besides the lines are staggered and cannot be matched. It indicates that in the damaging period of low cycle fatigue the material undergoes severe shear stress.

The angle between the lines and the fatigue load direction [001] is 50°. It consists with the $\{111\}<110>$ slip systems.

**4. Conclusions**

The fracture analysis of a Ni-based single crystal superalloy is proposed in the presented study. The fracture morphology showed that the specimens single-source cracked in LCF tests. Fatigue bands appeared at the crack propagation region are proved to be dependent on the secondary crystallographic orientation. The angle of fatigue bands increases with the increase of secondary orientation deviation. Cleavage surface at the final instant rupture region and slip lines near secondary crack tip indicate that this material damaged along $\{111\}<110>$ slip systems under shear stress.

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