Experimental investigation on fatigue crack growth of directional solidified superalloy with single hole

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Abstract: In order to study the fatigue crack growth of directional solidified superalloy with single hole, the fatigue crack growth test of DZ125 was carried out under different stress levels. The fracture morphology of the specimens were analyzed by field emission scanning electron microscope, and the relationship between stress and life was fitted. It is found that the stress concentration around the hole and the defects lead to the crack initiation near the maximum principal stress point. The da/dN - ∆K satisfies Paris formula well.

1. Introduction

Nickel based directional solidified superalloys are widely used in aeroengine turbine blades because of their excellent high temperature mechanical properties[1]. Due to the performance requirements of the engine, there are complex cavities and film cooling holes in the turbine blade[2]. These small holes or notches often become fatigue sensitive parts due to stress concentration. Therefore, the fatigue characteristics of the small holes or notches have always been a concern. DZ125 alloy is a kind of directionally solidified nickel based cast superalloy with high comprehensive properties. It has good comprehensive properties at medium and high temperatures and excellent thermal fatigue properties[3, 4]. At present, the research on DZ125 materials involves the interaction of fatigue and creep[5, 6], fracture characteristics[7], ultra-high cycle fatigue[8], the influence of different test sizes, orientations and phase angles, and dwell times[9] on thermomechanical fatigue life and welding mechanical properties. In the research on crack growth, Shi Yi et al.[10, 11] conducted high-temperature fatigue crack growth tests on DZ125 standard CT specimens, and studied the effects of temperature and material orientation on the crack growth rate. The results showed that high temperature significantly increased the crack growth rate. The material orientation has a weak effect on the crack growth rate at high temperature. For DZ125 structural parts with holes, Zhou Tianpeng et al.[12] conducted low cycle fatigue and load holding fatigue tests on small hole components, and the results showed that the crack initiation position was at the defect near the maximum stress point of small hole. However, the research on fatigue crack growth of superalloy with holes is relatively less, so it is necessary to study the fatigue crack growth of DZ125 structure with holes.

In this paper, for the directionally solidified nickel-based casting superalloy DZ125 material, the fatigue crack growth test at room temperature was carried out on the specimen, and the fracture morphology of the crack growth area of the specimen was observed with a field emission scanning electron microscope. Subsequently, according to the a-N curve of the fatigue crack growth test data, the relationship curve between the crack growth rate and the stress intensity factor was obtained, and the
undetermined parameters in the Paris formula were fitted. This study can provide a reference for the study of fatigue crack growth of superalloy structures with holes in the future.

2. Test materials and methods

2.1. Test materials

The material used in this test is the directionally solidified nickel-based casting superalloy DZ125. Its chemical composition is shown in Table 1. DZ125 is an orthotropic metal material, and its mechanical properties under [001] orientation are obviously better than those of the other two orientations. Therefore, the fatigue crack growth in the downward direction is mainly studied, that is, the length direction of the specimen is [001] orientation.

Table 1. Chemical composition of DZ125 nickel-based casting superalloy (specific gravity, %)

| C    | Cr | Ni | Co | W | Mo |
|------|----|----|----|---|----|
| 0.007~0.12 | 8.4~9.4 | Bal. | 9.5~10.5 | 6.5~7.5 | 1.5~2.5 |

| Al   | Ti | Fe | Ta | Hf | B  |
|------|----|----|----|----|----|
| 4.8~5.4 | 0.7~1.2 | ≤0.3 | 3.5~4.1 | 1.2~1.8 | ≤0.02 |

In this paper, a plate sample with a single circular hole is designed. The width of the sample is 14mm, the length is 90mm, the thickness is 2mm, and the hole diameter is 3mm. The hole making process of mechanical processing is adopted. The detailed size of the sample is shown in Figure 1.

![Figure 1. Physical and design drawings of the crack propagation specimen](image)

2.2. Test method

In this test, the fatigue crack growth test at room temperature is carried out according to the standard for fatigue crack propagation test of metallic materials ASTM-E647[13]. In order to reduce the test instrument error, all tests are completed on the same fatigue testing machine, and the test pieces are tightly fitted with mechanical clamping. The stress-controlled loading method is adopted, the test loading direction is [001] orientation, and the stress ratio is 0.1. The simplified load spectrum of the test is in the form of triangle wave. The loading program of crack propagation is the dead load increasing K method recommended by ASTM-E647.

3. Results and discussion

3.1 fatiue life

Table 2. fatigue life

| temperature/℃ | Stress ratio | Maximum stress/MPa | Life/cycle |
|---------------|-------------|---------------------|------------|
| 140           | 1345000     |                     |            |
| 150           | 1221800     |                     |            |
| 25            | 0.1         | 160                 | 991800     |
| 170           | 847300      |                     |            |
| 180           | 664700      |                     |            |


The fatigue life of the specimens at various stress levels is shown in Table 2. With the increase of stress, the fatigue life decreases gradually. The existing literature shows that the stress life relationship is power function, so the power function is used to fit the S-N data.

![S-N curve fitted by Basquin](image)

Figure 2. S-N curve fitted by Basquin

Fatigue life also analyzed on the basis of the Basquin[14] equation below:

$$\sigma_{max} = A(2N_f)^b$$  \hspace{1cm} (1)

The fatigue strength coefficient $A$ and the fatigue strength exponent $b$ are evaluated.

The S-N curve fitted by Basquin equation is shown in Figure 2. It can be seen from the figure that the experimental results are in good agreement with the fitted Basquin curve, and the fatigue strength constant and fatigue strength index are respectively $A = 2860.96$, $b = -0.38$, and correlation coefficient $R^2 = 0.96$. The fatigue limit of the test piece is analyzed by Basquin curve, and it can be calculated from the equation that the fatigue of DZ125 test piece with hole at room temperature is about 67 MPa.

3.2. fracture morphology

![Fracture morphology on the left side of hole](image)

Figure 3. Fracture morphology on the left side of hole
Figure 4. Fracture morphology on the right side of hole

Figure 3 and Figure 4 show the fracture morphology on both sides of the hole, Figure 3 shows the fracture morphology on the left side of the hole, and Figure 4 shows the fracture morphology on the right side of the hole. It can be seen from the figure that the fatigue crack of DZ125 at room temperature nucleates at the defect around the hole, and then the crack propagates to both sides. The fracture morphology can clearly distinguish the fatigue growth region and the instantaneous fracture region. The morphology of the fatigue growth area is irregular, uneven, smooth, and presents the characteristics of crisscross crystallographic planes on the whole, while the morphology of the instantaneous fracture area is relatively flat, rough, and roughly shows the dimple morphology. The crystal theory of metallic materials shows that the fracture related to plastic deformation and the slip caused by dislocation plug are the direct causes of crack formation. Therefore, the crack propagation tends to propagate along a certain slip plane, resulting in the crisscross phenomenon of crystallographic planes.

Figure 5 shows a partial enlarged view of the fracture. As shown in Figure 5 (a), the fatigue crack nucleates at the defects around the hole, and the source region tends to diverge outward. According to Ma Xianfeng et al.[15, 16], stress concentration and defects lead to crack nucleation. Figure 5 (b) shows that the internal cracks of the specimen propagate alternately along the crystallographic plane in general. Macroscopic fatigue steps are found on the fracture surface, and microscopic fatigue steps are found at the staggered position of crystallographic planes, as shown in Figure 5 (c). Figure 5 (d) shows the morphology of fracture instantaneous fracture zone. In the final stage of fatigue crack propagation, the length of crack is the largest and the effective cross section of specimen is the smallest. The failure mode of the specimen is inclined to tensile failure. The plasticity of the whole instantaneous fracture zone is obvious, which shows the ductile fracture morphology of dendrite fracture.
3.3. Fatigue crack growth rate relationship

The fatigue crack length under cyclic load is observed by optical microscope. The a-N curve under different stress levels is shown in Figure 6. It can be seen from Figure 6 that when the stress is large, the crack initiation life is short, the crack growth is fast, and the a-N curve is steep; when the stress is small, the crack initiation life is longer, the crack growth is slow, and the a-N curve is relatively gentle. The relationship between the fatigue crack growth rate and the variation of stress intensity factor was first given by Paris and Erdogan[17],

\[
\frac{da}{dn} = C(\Delta K)^m
\]

(2)

where \(a\) is the crack length, defined as the projection length perpendicular to the loading axis, \(\Delta K\) is the variation of stress intensity factor, \(C\) and \(m\) are the Paris parameters to be determined.

According to the theory of linear elastic fracture mechanics, \(\Delta K\) is calculated by the following formula:

\[
\Delta K = \Delta \sigma Y \sqrt{\pi a}
\]

(3)

where \(\Delta \sigma\) is the stress amplitude, \(\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}}\); \(Y\) is the geometric factor, which is a function of the crack length \(a\). For plate members with finite width and holes, the geometry factor is given by stress intensity factor handbook[18].

![Figure 6. a-N curves under different stress conditions](image)

![Figure 7. Fitted Paris curve](image)
Figure 7 shows the fitting curve between $\frac{da}{dN}$ and $\Delta K$ by Paris formula. It can be seen from the figure that the relationship between logarithmic crack growth rate and the variation amplitude of logarithmic stress intensity factor presents a linear correlation, which better meets Paris formula. The fitted Paris constant $C = 2.455\times10^{-12}$, $m = 6.185$, and linear correlation coefficient $R^2 = 0.8$. The data points in the near threshold area are below the straight line, and the data points in the fast expanding area are above the straight line. The overall trend is in line with the characteristics of Paris three stages.

4. Conclusion
In this paper, the crack growth test of DZ125 structural parts with holes at room temperature is carried out, and the following conclusions can be obtained by analyzing the fatigue life and growth laws:

1) At room temperature, the fatigue limit predicted by the Basquin equation of the DZ125 structure with holes used in the test is about 67MPa, and the stress life is roughly related to the power function, and the Basquin equation is used to fit the life-stress expression.

2) The crack propagation area of the fracture shows a macroscopic morphology with multiple crystallographic planes interlaced with each other and a microscopic morphology of fatigue steps, and the transient fracture area shows a ductile failure morphology of dendritic fracture.

3) The $\frac{da}{dN}$-$\Delta K$ relationship of DZ125 at room temperature satisfies the Paris law. The fitted constant $C=2.455\times10^{-12}$, $m=6.185$, and the linear correlation coefficient $R^2=0.8$.

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