Research Article

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Effect of different drilling techniques on high-cycle fatigue behavior of nickel-based single-crystal superalloy with film cooling hole

1 Introduction

The turbine is the largest component of thermal loads and mechanical loads in the aircraft engine; thus, the performance of the engine depends on the temperature of the turbine inlet [1]. The increasing turbine inlet temperature is an important means to improve engine performance. In recent years, the wide application of superalloy materials especially nickel-based single-crystal superalloy on turbine blades makes the inlet temperature of the turbine increase continuously [2–6]. However, the temperature resistance of the materials is limited [7]; the film cooling hole of turbine blade has been proven as an effective way to reduce the surface temperature of turbine blades. Consequently, the drilling technique of film cooling hole has become one of the key technologies of turbine blade manufacture. At present, laser drilling (LD), electrical discharge machining (EDM), and electric-stream machining (ESM) are widely used for film cooling holes [8], and different drilling techniques have their own advantages and disadvantages. LD and EDM are hot working techniques, but the ESM is a cold working technique. The drilling speed of LD is fast, but the recast layer and microcracks would be formed [9]. As for EDM, the recast layer is relatively thin than LD but there are still microcracks. ESM is based on electrochemical principles; hence, there is no recast layer, heat-affected zone, and microcracks.

The HCF fatigue caused by the vibration is inevitable during the service of the nickel-based single crystal turbine blades [10,11]. The integrity of the blade structure is damaged due to the presence of the film cooling hole, and it has been the weak links in the stress concentration and multi-axis stress states [12–16]. The drilling process might modify the original properties of the material around the hole and affect the mechanical properties. At the same time, the film cooling hole leaving on the surface of turbine blades will destroy the structural integrity of the material. Under the effect of porous interference, the local area of the film cooling hole becomes the multiple sites of the failure fracture. Hence, it is very important to study the life of the specimens with film cooling hole for the application of engine blade engineering.

The fatigue life of nickel-based single crystal blades with film cooling hole has attracted much attention from the researchers. Many researchers have studied the effect of different drilling techniques on material characterization. For
instance, Liu et al. [17] studied the mainstream manufacturing process of the film cooling hole and analyzed the effect of drilling processes on fatigue performance. Wen et al. [18] compared the creep life of thin-wall plate specimens with cooling holes with specimens without holes and studied the effect of cooling holes on the creep life. Kluev et al. [19] studied the effect of the EDM process on Inconel 718 and analyzed the factors of recast layer thickness. Gamage et al. [20] studied the influence of EDM parameters on the quality of the hole. Gemma and Phillips [21] predicted the life of different cooling hole configurations formed by LD, EDM, and electrochemical machining using fracture mechanics. However, the effect of different drilling techniques on the HCF properties of a nickel-based single crystal with film cooling holes has not been effectively carried out in the present literature.

The objective of the present work is to fill the gap in the literature, relating to the effect of different drilling techniques on HCF properties of a nickel-based single crystal with film cooling holes. The flat plate specimens of nickel-based single-crystal superalloy with film cooling holes were made by millisecond laser drilling (MSLD), EDM, and ESM. The effect of different drilling techniques and temperature on HCF properties was investigated.

2 Materials and methods

2.1 Experiment material

The second-generation single-crystal superalloy DD6 is used in the experiment. The single-crystal superalloy specimens with [001] orientation were cast by the helical crystal selection method and directionally solidified in the furnace of high-temperature gradient. The crystal orientations of the specimens were determined by the Laue X-ray back-reflection method. All the plates tested in this experiment had deviations within 5° from the perfect [001] direction.

Plate specimens with 14 holes are designed according to the complicated structure of the turbine blades. The schematic diagram of the plate is shown in Figure 1. The specimens with a single hole were introduced to study the effects of temperature on fatigue life. The schematic diagram of the plate is shown in Figure 2. The unit in Figures 1 and 2 is mm.

2.2 Experiment method

All the HCF tests were carried out on the servo-hydraulic material testing system (GPS-100), and the temperature was limited in ±5°C. The stress ratio R of minimum to maximum stress is 0.1, and the loading frequency is 90 Hz. The tests of specimens with 14 film cooling holes were conducted at 980°C in an ambient atmosphere. The tests of specimens with a single film cooling hole were conducted at 900°C, 980°C, and 1,050°C in an ambient atmosphere. The experimental program was stress-controlled with trapezoidal load waveforms which is shown in Figure 3. All the test data were recorded by the computer automatically. Fracture surfaces and micrographs of the holes were observed using scanning electric microscopy (SEM; Hitachi S-4800) after ultrasonic cleanout.

3 Results and discussion

3.1 Microstructure of the film cooling hole

Micrographs of film cooling hole in different drilling techniques are shown in Figure 4. The micrographs of
MSLD, EDM, and ESM are shown in Figure 4a–f, respectively. It can be seen from Figure 4 that both MSLD and EDM have recast layers around the film cooling hole whereas ESM does not. The reason is that the MSLD and EDM are all belonged to hot working, but the ESM is cold working. Figure 4a shows that the recast layer thickness of MSLD is about 43 µm. The high temperature in the processing process separates a large number of elements around the hole, and the final major residual component is carbides and oxides of cobalt and nickel. Consequently, the outer layer materials of the recast layer are loose, there are several microcracks such as Letter A in the recast layer as shown in Figure 4b, and Letter B is a magnify micrograph of Letter A. It is obvious that there are microcracks existing in the recast layer during the MSLD process. The microcracks are likely to become the original positions of the high-cycle fatigue (HCF) cracks of the material and gradually expand under the continuous action of the cyclic load. As for EDM, the recast layer is about 35 µm, and it is thinner than MSLD. No obvious microcracks are observed in the inner wall of the film cooling hole.

The micrograph of ESM is significantly different from the MSLD and EDM. The film cooling hole of ESM shows regular round, and the inner wall is smoother. There is no recast layer, and the heat-affected zone can be found around the hole. As ESM is mainly through the dissolution of the anode metal to achieve the hole, the recast layer and microcracks can be avoided.

3.2 Effect of different drilling techniques on fatigue strength

S–N curves of fatigue testing for MSLD, EDM, and ESM specimens with 14 film cooling holes at 980°C are shown in Figure 5. The triangles, squares, and circles are representing MSLD, EDM, and ESM, respectively. The arrows indicate that the specimens were no failures during the tests. It can be seen from Figure 5 that S–N curves of different drilling techniques show a general trend that the fatigue strength decreases with the stress increasing. Moreover, at the same stress amplitude, the fatigue life of the ESM specimens is longer than that of the MSLD and EDM. The fatigue limit of MSLD is 353 MPa, while EDM is 359 MPa and ESM is 378 MPa. The fatigue limit of ESM is higher than other drilling techniques. The fatigue limit of ESM is higher than that of MSLD 25 MPa that is 7.1%. Meanwhile, the fatigue limit of ESM is higher than that of EDM 19 MPa that is 5.3%.

The fatigue limit of the material is determined by the up-and-down fatigue test method. The tests carried out
in the present study are in accordance with the test standard (metal material axial loading fatigue test method) [22]. The fatigue limit \( \sigma_D \) can be written as follows:

\[
\sigma_D = \frac{1}{n} \sum_{i=1}^{m} V_i \sigma_i \tag{1}
\]

where \( m \) is the total number of valid tests, \( N \) is the stress level series, \( V_i \) is the number of tests under the \( i \) stress level, and \( \sigma_i \) is the stress level \( i \).

The S–N curves were obtained by non-linear fitting with the Basquin equation [23], which can be written as follows:

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**Figure 4:** Micrographs of film cooling holes (a and b) MSLD, (c and d) EDM, and (e and f) ESM.
σd is the alternating stress, σf′ is the fatigue strength coefficient, Nf is the number of cycles to failure, and b is the Basquin exponent.

The parameters of the Basquin equations and the fatigue limits of different drilling techniques are listed in Table 1.

Table 1: Parameters of the Basquin equations and fatigue limits

<table>
<thead>
<tr>
<th>Technique</th>
<th>σf′/MPa</th>
<th>b</th>
<th>σd/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSLD</td>
<td>868</td>
<td>-0.054</td>
<td>353</td>
</tr>
<tr>
<td>EDM</td>
<td>1,452</td>
<td>-0.083</td>
<td>366</td>
</tr>
<tr>
<td>ESM</td>
<td>2,535</td>
<td>-0.115</td>
<td>378</td>
</tr>
</tbody>
</table>

\[
\sigma_d = \sigma_f'(2N_f)^b, \tag{2}
\]

where \(\sigma_d\) is the alternating stress, \(\sigma_f'\) is the fatigue strength coefficient, \(N_f\) is the number of cycles to failure, and \(b\) is the Basquin exponent.

The effect of different drilling techniques on HCF behavior is discussed in this paper. Figure 5 shows the S–N curve of different drilling techniques specimens at 980°C.

3.3 Fractography

To understand the behavior of fatigue crack initiation and propagation clearly, the failed specimens fracture surfaces with 14 holes of different drilling techniques were examined.

Figure 6 shows the macroscopic fracture morphology of the MSLD specimen. Figure 6a is a fracture profile of the specimen. It can be seen that under the action of high temperature and alternating load, crack initiate from the edge of the middle hole at first and then propagate along the path between the hole. Figure 6b is a fracture surface near the hole. We can see that the fracture surface of the hole is made up of several inclined planes, and the normal direction of A plane (001) is parallel to the loading direction. The angle between the normal direction of B plane and loading direction is 45°–50°; it can be confirmed from the crystal theory that B plane is (111) plane. Generally speaking, if there is no interaction between porous, the cracks will propagate along (001). But the stress is complex because of the several holes under interaction, then the propagation mechanism may be different.

The fracture morphologies of MSLD, EDM, and ESM are shown in Figures 7–9, respectively. From the fracture morphologies, it can be concluded that different drilling techniques have similar morphologies. And, there are multiple fatigue sources for the fracture morphology of the specimens after HCF tests at 980°C under different stress amplitudes. During the crack propagation, fatigue cracks expand from outmost surfaces deep into interior along the primary slip plane under the alternative stress. Figure 7a is the macroscopic fracture morphology of MSLD, and there are two different areas indicated by 1 and 2. Figure 7b is the magnify micrograph of hole 1 in Figure 7a. It can be seen that...
the cracks propagate along the [001] planes and the bright shell area can be found, but no obvious river strip and ladder fracture characteristics exist. Thus, we can infer that the area surrounds the film cooling hole is the crack extension area.

Figure 7: Fracture morphology of MSLD: (a) macroscopic fracture morphology, (b) middle hole fracture morphology, (c) edge hole fracture morphology, (d) shell area, and (e) the EDS analysis of oxides.
Figure 7c is the magnify micrograph of hole 2 in Figure 7a. As can be seen from Figure 7c that the letter A which has similar morphologies with hole 1 is the crack propagation area of hole 2. However, the length of the crack propagation area is only 0.4335 mm. The letter B in Figure 7c is an instant rupture zone which is along the \{111\} planes and has the ladder fracture characteristics. Figure 7d is the magnify micrograph of the shell area in Figure 7b. It can be seen from Figure 7d that the crystal grain is complete and slightly oxidized. The EDS analysis of oxides in Figure 7d is shown in Figure 7e. Figure 8 shows the macroscopic fracture morphology of the EDM specimen. As can be seen, it is obviously different from the fracture morphology of MSLD. There is no shell area and it si typical crisp fracture. Figure 9 shows the macroscopic fracture morphology of the ESM specimen. We can see that there are many tear ridges along the hole edge, and the crack propagates from the hole edge to both sides of the hole. In summary, typical fatigue morphology includes fatigue source area, crack propagation area, and instant rupture zone. There is no recast layer and a heat-affected zone can be found around the hole of ESM. As ESM is mainly through the dissolution of the anode metal to achieve the hole, the recast layer and heat-affected zone can be avoided. Fewer microcracks can be found around film holes. Fatigue is most sensitive to defects such as cracks; therefore, ESM is better than the others.
3.4 Effect of temperature on fatigue strength

S–N curves of fatigue testing for EDM specimens with single film cooling holes at 900, 980, and 1,050°C are shown in Figure 10. According to Figure 10, the temperature makes a significant influence on the fatigue limit. As the temperature increases, the fatigue life decreases gradually. The fatigue limit of the specimen is 472 MPa at 900°C. The fatigue limit of specimen decreased to 42 MPa, i.e., 430 MPa with an attenuation rate of 2.25 MPa/10°C while the temperature increased from 900 to 980°C. But the fatigue limit of specimen sharply decreased when the temperature is 1,000°C. The fatigue limit of the specimen is 293 MPa at 1,050°C. Comparing the fatigue limit of the specimen at 1,050 to 980°C, it can be found that the fatigue limit decreased to 137 MPa with an attenuation rate of 19.57 MPa/10°C. Consequently, the attenuation rate of the fatigue limit increases with the temperature rising.

The parameters of the Basquin equations and the fatigue limits of different drilling techniques are listed in Table 2.

As for the specimens with a single hole, the film cooling hole destroyed the integrity of the structure, and as a result, the microcracks will occur around the hole. The HCF tests of specimens without any hole were carried out, and the fracture morphology is shown in Figure 11. It can be seen that the severe stress concentration is first generated at the casting defect, which is the primary location of crack initiation. For specimens with a film cooling hole, the cracks occur around the hole. For specimens without any hole, the cracks occur at the defects.

The crack initiation has a close relationship with temperature. In engineering practice, $q$ is commonly used to characterize the notch sensitivity of structures. Usually, the notch sensitivity $q$ was defined as follows [24]:

$$ q = \frac{K_f - 1}{K_t - 1} $$

(3)

where $K_f$ is the fatigue notch factor and $K_t$ is the theoretical stress concentration factor, which defined as follows:

$$ k_t = \frac{\sigma_R}{\sigma_H}, \quad k_t = \frac{\sigma_{\text{max}}}{\sigma_0}, $$

(4)

where $\sigma_R$ is the fatigue limit of the smooth specimen, $\sigma_H$ is the fatigue limit of the specimens with film cooling holes, $\sigma_{\text{max}}$ is the maximum local stress, and $\sigma_0$ is the principle stress.
The value of $q$ varies from $q = 0$ or no notch effect to $q = 1$ or full theoretical effects. The notch sensitivity of the specimens with a single hole under different temperatures is listed in Table 3. It can be seen from Table 3, the notch sensitivity increases with the temperature increases, and the notch sensitivity at 900, 980 and 1,050°C is 0.012, 0.085, and 0.027, respectively. The higher the notch sensitivity is, the easier the crack initiation around the film cooling hole and the lower of the fatigue life.

To investigate the microstructure changes after HCF deformation under different temperatures, the γ/γ′ microstructure of the specimens with a single hole was observed by SEM. The microstructure of the specimens at 980°C is shown in Figure 12. The microstructure of the original specimen is shown in Figure 12a, which has the typical phase of γ and γ′ [25]. The microstructure of the specimen after the HCF test is shown in Figure 12b. The images are taken from the position shown in Figure 13. The change of γ′ shape is related to time and temperature. Generally, the longer the time, the higher the temperature, and the more obvious the change of γ′ shape is. The change of γ′ shape generally occurs in the creep process. For high-cycle fatigue, due to the short time and low stress, no obvious plastic deformation can be observed. Although there is stress concentration, it has little effect on the change of γ′ shape. Comparing Figure 12a and b, it is interesting to notice that the shape of γ′ changed severely after the HCF test. The shape of γ′ changed from regular cube to irregular cube. The γ′ particles show a tendency to dissolve into the γ matrix. The change of γ′ shape only occurred in some localized areas closed to the specimen surface near the hole where the maximum stress amplitude was implemented.

4 Conclusion

The effect of different drilling techniques on HCF lives of single-crystal superalloy DD6 specimens with 14 film cooling holes at 980°C was investigated. The specimens with a single hole were also used to study the HCF properties under different temperatures. The main conclusions could be drawn as follows:

1) The fatigue strength decreases with the stress increasing for different drilling techniques. At the same stress amplitude, the fatigue life of the ESM specimens is longer than that of the MSLD and EDM.

2) At 980°C, the fatigue limit of ESM is 378 MPa, while EDM is 359 MPa and MSLD is 353 MPa.

3) The fracture characteristics of different drilling techniques are similar that all belong to the multi-source fracture. The fracture includes three parts: the cracks sources around the film cooling hole, the propagation zone along the {001} planes, and the instant rupture zone along {111} planes.

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Figure 12: Microstructures of the specimens: (a) original specimen and (b) after the HCF test.

Figure 13: The position where the images are taken from.
Author contributions: Zhijin Zhang performed the data analyses and wrote the manuscript; Mingqi Zhang contributed to the conception of the study.

Conflict of interest: The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Data availability statement: All data generated or analyzed during this study are included in this article.

References


