A Creep-Fatigue Interaction Model of Nickel-Based Single Crystal Superalloys under Multiaxial Stress Conditions

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Abstract: This study investigates the low-cycle fatigue (LCF) behavior of nickel-based single-crystal superalloy DD3 at 620°C, considering both smooth and notched specimens. A novel LCF life model is proposed, incorporating the mean stress effect and based on crystallographic theory. The model describes LCF life as a power function of the maximum resolved shear stress of activated slip systems, with parameters obtainable from smooth round specimens at various stress levels. Validation of the model is demonstrated through excellent agreement with experimental results from additional smooth and notched round specimens, further supported by SEM analysis of fracture surfaces. The research also provides insight into the deformation mechanisms of nickel-based single-crystal superalloys under multiaxial stress states.

Keywords: flexible multibody dynamics, impact with friction, momentum balance equations, routh's diagram, poisson's hypothesis

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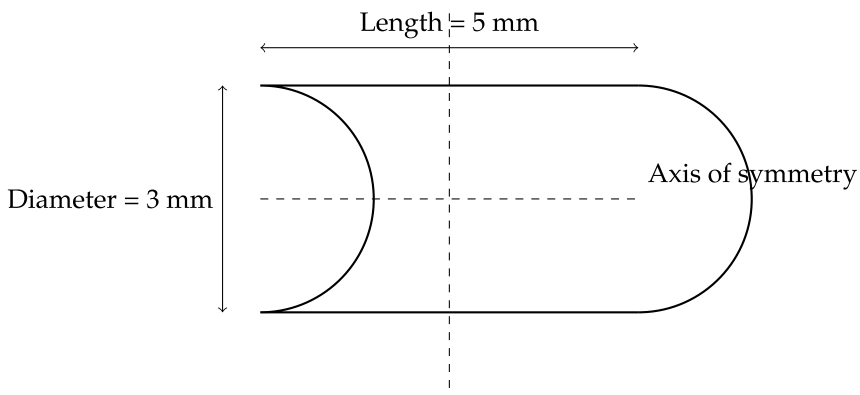
1. Introduction

Nickel-based single-crystal superalloys have become the material of choice for gas turbine blades due to their exceptional creep, fracture, and fatigue properties, which surpass those of conventionally cast alloys. The absence of grain boundaries in single crystals is responsible for their superior high-temperature properties, but also leads to anisotropic mechanical properties. Turbine blades are subjected to complex multiaxial stress states due to their intricate shape, temperature gradients, and aerodynamic loading. This is particularly pronounced in the blade root region, where the blades connect to the turbine disc [1].

Understanding the low-cycle fatigue (LCF) behavior of nickel-based single-crystal superalloys at high temperatures is crucial for ensuring the reliability and performance of gas turbines. Previous studies have investigated the fatigue behavior of single-crystal superalloys, such as CMSX-2 and Rene N4, focusing on microcrack growth, defect size and location, and crack growth. Additionally, research has explored the influence of crystallographic orientations on fatigue-creep behavior [2].



Smooth round specimen

Building on this existing knowledge, the present study aims to simulate the LCF behavior of blade roots using a set of notched specimens. By combining experimental results with finite element analysis, a novel LCF life model is proposed for multiaxial stress states. Furthermore, scanning electron microscopy (SEM) observations of fracture surfaces provide valuable insights into the deformation and damage micromechanisms of nickel-based single-crystal superalloys at high temperatures. This research contributes to the development of more accurate life prediction models for gas turbine blades, ultimately enhancing their performance and lifespan.

2. Procedure

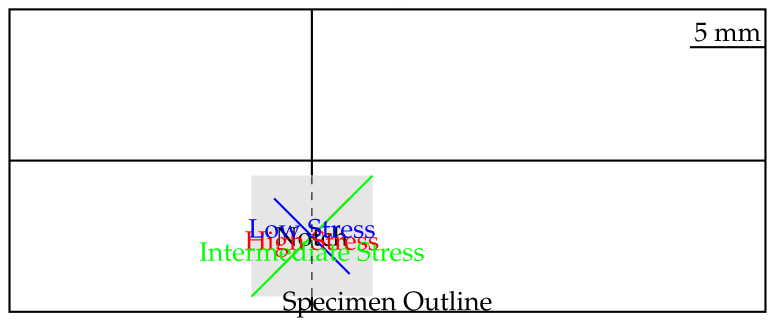
The material used in this study is DD3, a trademark of Beijing Institution of Aeronautic Material. Round bars with longitudinal axes within 5° of [0 0 1] were provided, from which standard smooth round specimens and notched round specimens (U-shape and V-shape) were machined. The smooth round specimen configuration is shown in Fig. 1, while the notched specimens have the same configuration with the addition of a notch in the middle of the bars, with geometries. A total of six notched specimens were studied.

Low-Cycle Fatigue (LCF) experiments were conducted at 520°C in air using an MTS-810 testing machine, with a temperature deviation in the gauge area maintained within ±2°C. All experiments were performed under load/stress control, with a testing frequency of 0.17 Hz. The testing procedure involved heating the specimens to 620°C, setting the testing machine to load/stress control mode, initiating the LCF testing, and continuing until specimen failure, while maintaining the temperature within ±2°C throughout the process.

3. Results

The below figure and table presents the Low-Cycle Fatigue (LCF) records and results of smooth round specimens tested at 520°C. The table lists the specimen number, applied stress (αmax and αmin in MPa), and the average number of cycles to failure. Two specimens were tested for each case.

Notched Specimen



Specimen No.	α_{max} (MPa)	α_{min} (MPa)	Average Number of Cycles
g-1	500	25	>65700
g-2	640	32	>72633
g-3	500	-900	13423
g-4	650	-550	2041
g-5	800	-400	5334

Table 1. LCF Records and Results of Smooth Round Specimens at 520°C

The below table LCF Records and Results of Notched Round Specimens at 620°C, the LCF records and results of notched round specimens tested at 520°C. The table lists the specimen number, applied stress (αmax and αmin in MPa), and the average number of cycles to failure. Two specimens were tested for each case.

Specimen No.	α_{max} (MPa)	α_{min} (MPa)	Average Number of Cycles
Notch 1	700	35	3639
Notch 2	700	35	10804
Notch 3	700	35	42860
Notch 5	900	40	1404
Notch 6	900	40	5083
Notch 7	900	40	2609

Table 2. LCF Records and Results of Notched Round Specimens at 520°C

4. Discussion

The crystallographic slip theory is assumed to be applicable for nickel-based single crystals at 620°C. This theory is based on the relationship between the resolved shear stress (τ) and resolved shear strain (γ) of the activated slip systems [3]. The resolved shear stress of a slip system (β) can be obtained using the following equation:

$$\tau(\beta) = \alpha : P(\beta)$$

where α is the stress tensor, and $P(\beta)$ is a parameter that can be obtained from:

$$P(\beta) = \frac{1}{2}\left(m(\beta)n(\beta)^{\mathrm{T}} + n(\beta)m(\beta)^{\mathrm{T}}\right)$$

where $n(\beta)$ and $m(\beta)$ are the unit vectors normal to the slip plane and along the slip direction of the slip system (β), respectively.

A power-law life model is assumed for the nickel-based single-crystal superalloys based on the crystallographic theory:

$$\left(\frac{\tau_{\max}}{2}\right)^2 = AN_f^b$$

where $\tau_{\max}$ is the maximum resolved shear stress amplitude of all activated slip systems, A and b are parameters, and N_f is the fatigue life.

To consider the mean stress effect, a modification of the power-law life model is proposed:

$$\left(\frac{\tau_{\max}}{2}\right)^2 = AN_f^b\left(1 - \left(\frac{\tau_m}{\tau_b}\right)^2\right)$$

where τ_m is the mean resolved shear stress on the slip system corresponding to maximum shear stress, and τ_b is the resolved shear stress corresponding to the ultimate tensile strength.

The parameters of the power-law life model are derived from the experimental results of specimens g-3 and g-4:

$$\text{For specimen g-3:} \quad \left(\frac{\tau_{\max}}{2}\right)^2 = 285.8\,\text{MPa}$$

$$\text{For specimen g-4:} \quad \left(\frac{\tau_{\max}}{2}\right)^2 = 306.2\,\text{MPa}$$

The parameters are found to be $A = 449.2$, $b = -0.04888$.

The experimental results of specimen g-5 are used to validate the LCF life model:

$$\left(\frac{\tau_{\max}}{2}\right)^2 = 285.8\,\text{MPa}$$

Using the power-law life model, the predicted LCF life of specimen g-5 is:

$$N_f = 5352$$

which is in good agreement with the experimental result of 6234, with an error of 16.5

For notched round specimens, the finite element method (FEM) is used to provide the stress distribution [4]. The resolved shear stress contour plots and true stress versus strain relation of the notch region are obtained.

The LCF life model is validated by the experimental results of notched specimens using the same approach as for smooth round specimens. The model parameters obtained from smooth round specimens are used to predict the LCF life of notched specimens [5].

The following approach is employed to analyze the LCF life model prediction lives of notched specimens:

1. The stress versus strain relationship is obtained by tensile testing [6].
2. The region at greatest risk in different notch specimens is determined by crystallographic finite element analysis [7].
3. Based on crystallographic theory, the resolved shear stresses are computed corresponding to the maximum and minimum loadings of the greatest risk element [8].
4. The maximum resolved shear stress is calculated using:

$$\tau_{\max} = \max(\tau(\beta))$$

5. The resolved shear stress amplitude and the mean resolved shear stresses corresponding to the maximum resolved shear stress are calculated.
6. The LCF life model is used to predict the LCF life of notch specimens based on the parameters obtained from the smooth round specimens.

Mathematically, the LCF life model can be expressed as:

$$N_f = \left(1 - \left(\frac{\tau_m}{\tau_b}\right)^2\right) \cdot \left(A \cdot \left(\frac{\tau_{\max}}{2}\right)^{-b}\right)$$

where N_f is the fatigue life, τ_m is the mean resolved shear stress, τ_b is the resolved shear stress corresponding to the ultimate tensile strength, A and b are parameters, and $\tau_{\max}$ is the maximum resolved shear stress amplitude.

The model parameters A and b are obtained from the experimental results of smooth round specimens, and the ultimate tensile strength is obtained from tensile testing. The mean resolved shear stress and maximum resolved shear stress amplitude are obtained from the finite element analysis of the notched specimens.

5. Conclusion

In this study, a low-cycle fatigue (LCF) life model was developed for nickel-based single-crystal superalloys at 620°C. The model is based on the crystallographic slip theory and takes into account the mean stress effect. The model parameters were derived from the experimental results of smooth round specimens, and the model was validated by the experimental results of notched round specimens. The results show that the LCF life model can accurately predict the fatigue life of both smooth and notched specimens. The model can also capture the effect of mean stress on fatigue life. The finite element analysis of the notched specimens shows that the model can be used to predict the fatigue life of complex geometries.

The LCF life model developed in this study can be used to predict the fatigue life of turbine blades made of nickel-based single-crystal superalloys. The model can also be used to optimize the design of turbine blades and to reduce the risk of fatigue failure. Overall, this study demonstrates the potential of using crystallographic slip theory to develop LCF life models for nickel-based single-crystal superalloys. The study also highlights the importance of considering the mean stress effect in LCF life modeling. Future work can focus on extending the LCF life model to other temperatures and loading conditions. Additionally, the model can be used to study the effect of other factors, such as oxidation and creep, on the fatigue life of nickel-based single-crystal superalloys.

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