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Fatigue life modeling of a single crystal superalloy and its thin plate with a hole at elevated temperature

Chengli Dong *, Huichen Yu *, Ying Li

Beijing Key Laboratory of Aeronautical Materials Testing and Evaluation, Science and Technology on Advanced High Temperature Structural Materials Laboratory, AVIC Beijing Institute of Aeronautical Materials, Beijing 100095, China

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ABSTRACT

Many low cycle fatigue (LCF) experiments of a second generation single crystal (SC) nickel-base superalloy and its thin plate with a hole are carried out to investigate the effects of crystallographic orientation and stress concentration on the LCF life. The local strain approach and two kinds of modified anisotropic models we proposed are employed to predict the fatigue lives for the SC superalloy and its thin plate with a hole. The results show that the LCF lives of the SC superalloy and its thin plate with a hole have strong crystallographic orientation dependence; the local strain approach fails to predict the fatigue lives but the two kinds of modified anisotropic models are able to predict the fatigue lives for the SC superalloy and its thin plate with a hole. However, compared with the modified anisotropic model only considering the interaction of shear strains, the modified one considering both interaction of shear strains and coupling of normal and shear strains has better predicted accuracy.

1. Introduction

Compared with polycrystalline and directionally solidified (DS) superalloys, the SC superalloy has better thermal, fatigue and creep properties at elevated temperature, thus it is increasingly required in the manufacture of severely stressed structural parts such as high-pressure turbine blades of the modern aeroengines [1–3]. Nickel-base SC superalloy is a two-phase material made of cuboidal γ' dispersion strengthening particles and face-centered cubic γ matrix [4–6]. However, the absence of grain boundaries in SC superalloy also leads to high material anisotropy which would produce orientation-dependent material response [7]. In order to fully exploit the advantages of the SC superalloy, the life models should be proposed to predict the orientation-dependent fatigue life at elevated temperature.

Up to now, there are some investigations on how to model and predict the fatigue life of anisotropic materials. Orientation factor [8–10] and critical plane [11–13] based methods are two main approaches employed to predict the fatigue life for the anisotropic superalloys. Due to both simplicity and convenience, the orientation factor based methods are widely used by engineers. The orientation factor predicting the arbitrary elastic modulus of anisotropic materials is employed to obtain the equivalent strain range in the special crystallographic orientation, which is based on the essential assumption that the effect of orientation on LCF life is similar to that on Young's modulus [12]. However, yield properties are not taken into account in the orientation factor based methods, so the orientation factor based methods are only suitable to predict the fatigue life of the materials in the elastic region rather than in the plastic region. The critical plane based methods which could predict not only the fatigue life but also the initiation and propagation have been proposed for multi-axial fatigue [14]. There is a two-step process required to use the critical plane based methods to analyze the fatigue behavior. Firstly, the stress–strain response on the critical planes should be determined by analytical or numerical solutions. Secondly, the accumulated fatigue damage is calculated based on the stress–strain response on critical planes. Generally, the crystallographic slip planes are considered as the critical planes, but the crystallographic slip planes activated are difficult to determine [15]. Even assuming that the activated crystallographic slip planes have been determined, the damage parameters on these critical planes are hard to be selected to correlate the fatigue life.

This paper is devoted to explore the life modeling of a second generation SC superalloy and its simple structure (*i.e.* thin plate with a hole). The work presented here develops two kinds of anisotropic models based on Mücke's approach [16]. Firstly, LCF experiments of the SC superalloy and its thin plate with a hole are

* Corresponding authors at: P.O. Box 81-23, Huanshan cun, Haidian district, Beijing 100095, China. Tel.: +86 10 62496718; fax: +86 10 62496733.
E-mail addresses: dcldong@buaa.edu.cn (C. Dong), yhcyu@126.com (H. Yu).

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carried out at 760 °C. Secondly, two kinds of modified anisotropic models are proposed to predict the fatigue lives. Thirdly, the two kinds of modified anisotropic models are validated by comparing the prediction with the test data, and then compared to each other to demonstrate their predicted accuracy.

2. Material and experimental procedure

2.1. Material description

The material studied here is a SC nickel-base superalloy with high γ' volume fraction of approximate 65%. The nominal chemical compositions (wt.%) of the material are listed in Table 1. SEM image of the cross section of the SC superalloy with [0 0 1] orientation after heat treatment is shown in Fig. 1. The representative microstructure consists of uniform cuboidal γ' particles in the face-centered cubic γ matrix. The γ'/γ arrangement in the whole volume is quite regular with the mean size of the γ' particles about 400 nm. The SC superalloy is directionally solidified along the natural dendrite orientation [0 0 1] in the form of SC cylinder 15 mm in diameter and 100 mm in length. The same size cylinder is also cast with an axial direction near [0 1 1] or [1 1 1]. The crystallographic orientation of the round bar is measured by Laue back reflection X-ray technique and the maximum deviation of the rod axis from [0 0 1], [0 1 1] and [1 1 1] is laid within 10 degree. All of the round bars have experienced the following solution and aging heat treatments: 1290 °C/1 h + 1300 °C/2 h + 1315 °C/4 h/AC + 1120 °C/4 h/AC + 870 °C/32 h/AC, (AC: air cooling). The simple structure studied here is the thin plate with a hole which produces the stress concentration near the hole. Actually, the thin plate is employed to simulate the thin-walled effect and the small hole is used to generate the stress/strain concentration of the air-cooled hole of the turbine blade.

2.2. Experimental procedure

Button-ended cylindrical specimens with a gauge diameter 6 mm, gauge length 14 mm and total length 90 mm are machined from heat-treated bars. The detailed size of the thin plate with a hole is shown in Fig. 2. The crystallographic orientations of [0 0 1], [0 1 1] and [1 1 1] are aligned parallel to the specimen axis. The LCF tests referred to the Standard Test Method GB/T15248-2008 [17] are performed on a closed-loop servohydraulic test machine, *i.e.* Shimadzu EHF-100KN-20L. The LCF load is controlled by the strain ratio $R_\varepsilon = -1$ at a constant strain rate of 5×10^{-3}/s. These LCF tests are carried out at 760 °C and the temperature variation in the radiation furnace is kept within 2 °C over the specimen gauge length. The detailed high temperature LCF test matrix of the SC superalloy and its thin plate with a hole is listed in Table 2. The tensile tests of the SC superalloy are conducted by INSTRON universal tensile machine to obtain the elastic constants at 760 °C as listed in Table 3.

3. The modified anisotropic model for the SC materials

3.1. Anisotropic elastic stress–strain response of SC materials

For anisotropic materials, the loading in arbitrary orientations and multiaxial load conditions are increasingly concerned by the researchers and engineers. One of the fatigue life models for anisotropic materials is proposed by Mücke and Woratat [16]. However,

Table 1
Nominal chemical compositions of the SC superalloy (wt.%).

C	Cr	Co	W	Mo	Al	Nb	Ta	Re	Hf	Ni
0.01	4.4	9.0	8.0	1.8	5.8	0.6	7.2	2.2	0.1	Bal.

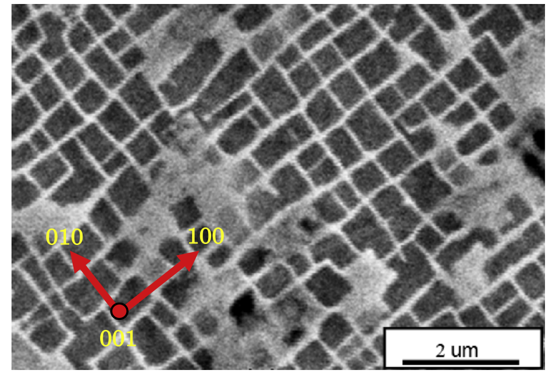

Fig. 1. Representative microstructure of the SC superalloy.

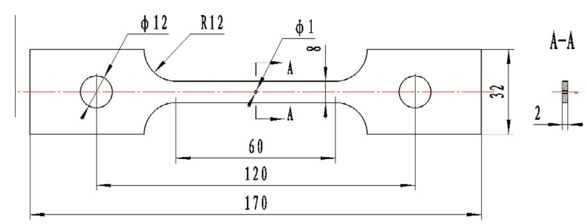

Fig. 2. The detailed size of the thin plate with a hole.

Table 2
High temperature LCF test matrix of the SC superalloy and its thin plate with a hole.

Specimen type	Strain ratio	Orientation	Strain range (%)
SC superalloy	−1	[0 0 1]	1.4, 1.6, 1.8, 2.0
	−1	[0 1 1]	0.9, 1.0, 1.2, 1.4, 1.6, 2.0
	−1	[1 1 1]	0.5, 0.6, 0.8, 1.0
SC structure	−1	[0 0 1]	0.3
	−1	[0 1 1]	0.3
	−1	[1 1 1]	0.3

the anisotropic life model they proposed is only employed to predict the fatigue life for DS materials. In this study, their theory is modified to predict the fatigue life for SC materials.

The load coordinate system is usually not consistent with the crystallographic coordinate system. The elastic stress–strain response can be obtained by establishing the transform relationship between the load coordinate system and crystallographic coordinate system.

$[b_1\, g_1\, h_1]$, $[b_2\, g_2\, h_2]$ and $[b_3\, g_3\, h_3]$ are the direction cosines between the load coordinate system and crystallographic coordinate system, and the coordinate transform is defined as

$$[\lambda] = \begin{bmatrix} b_1 & g_1 & h_1 \\ b_2 & g_2 & h_2 \\ b_3 & g_3 & h_3 \end{bmatrix} \tag{1}$$

where $[\lambda]^{-1} = [\lambda]^T$.

The anisotropic elastic response in the principal stress coordinate system can be generally expressed as

$$[\varepsilon] = [S][\sigma] \tag{2}$$

where S represents the elastic compliance matrix defined as

$$[S] = \begin{bmatrix} 1/E & -v/E & -v/E & 0 & 0 & 0 \\ -v/E & 1/E & -v/E & 0 & 0 & 0 \\ -v/E & -v/E & 1/E & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G \end{bmatrix} \tag{3}$$