International Journal of Fatigue 83 (2016) 335–343

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Effects of secondary orientation on crack closure behavior of nickel-based single crystal superalloys

Wenhui Qiu [a], Zhiwu He [a], Ya-Nan Fan [a], Hui-Ji Shi [a,*], Jialin Gu [b]

[a] AML, School of Aerospace Engineering, Tsinghua University, Bejing 100084, PR China
[b] School of Material Science and Engineering, Tsinghua University, Bejing 100084, PR China

A R T I C L E I N F O

Article history:
Received 12 January 2015
Received in revised form 29 September 2015
Accepted 2 November 2015
Available online 7 November 2015

Keywords:
Secondary orientation
Crack closure
Nickel-based single crystal superalloy
In-situ SEM fatigue tests

A B S T R A C T

The crack closure behavior of a nickel-based single crystal (SC) superalloy was studied based on in-situ SEM fatigue tests. Specimens in two different secondary orientations were tested at 600 °C. A model considering the anisotropy of SC superalloys was developed to analyze crack closure behavior. The results show that specimens in two orientations exhibit different cracking modes. For specimen [001]/[010], roughness-induced crack closure effect is dominant in crack closure behavior and crack closure effect is constant during crack propagation process. However, for specimen [001]/[110], plasticity-induced crack closure effect is dominant in crack closure which becomes enhanced as crack grows.

1. Introduction

Since the pioneering work of Elber [1] in the 1970s, many studies have been done on the mechanism of crack closure and its effects on fatigue crack growth (FCG). It has been realized that crack closure, which denotes the premature contact of the crack surfaces in the unloading sequence, is induced by plasticity, roughness, oxide, etc. [2]. Davidson [3] used high resolution microscopy techniques to investigate plasticity-induced closure and found that crack opening load magnitude depended upon the resolution with which it was measured. Bowman et al. [4] proved that closure measurements required good machine alignment and the test system should produce linear load displacement curves.

Generally, experimental techniques employed for crack closure determination fall into two categories, i.e. direct and indirect methods, and scanning electron microscopy (SEM) observation is one of the common direct methods [5]. Recently, there are increasing researches focusing on crack closure behaviors of small fatigue cracks based on in-situ observations by SEM. Zhang et al. [6] investigated crack closure behaviors of an aluminum alloy by SEM, and found that there existed a peak value in crack closure stress in short crack growth stage, afterwards the crack closure stress decreased and approached asymptotically to a constant value. Halliday et al. [7] made in-situ SEM measurements and observations of crack tip opening displacement (CTOD) during unloading process of small mixed-mode fatigue cracks. They reported that the level of Mode II closure was generally less than that for the Mode I component, leading to more crack growth in Mode II produced by the same nominal load range. Liu et al. [8–10] conducted in-situ SEM testing and imaging analysis to investigate the crack closure of small fatigue cracks under different stress ratios, and the results showed that the crack opening stress level increased as the stress ratios increased. Tu et al. [11] reported that the crack closure level of small fatigue cracks was strongly dependent on the crack size and the local tortuosity of the crack path.

Nickel-based single crystal (SC) superalloys are widely used as the material for hot sections of aircraft turbines and industrial gas turbines, taking place of conventional casting superalloys since 1980s [12]. The elimination of grain boundaries helps to reduce the number of cracks initiated from grain boundaries and improve the fracture and fatigue properties of superalloys especially at high temperature [13,14]. However, the reduction of grain boundaries leads to the anisotropy of SC superalloys. The effect of orientation on notch/crack-tip plasticity in SC superalloy has attracted a great interest recently, especially secondary orientation, which denotes the crack propagating direction. Arakere et al. [15,16] illustrated the strong dependence of the plastic zone size and the slip patterns on the secondary orientation of SC superalloy notches based on experiments and numerical simulations. Biswas et al. [17] conducted a combined experimental and numerical study on

---

* Corresponding author.
E-mail addresses: wendifen1@126.com (W. Qiu), shihj@mail.tsinghua.edu.cn (H.-J. Shi).

http://dx.doi.org/10.1016/j.ijfatigue.2015.11.004

interaction between a notch and voids in aluminum SC and found that crystallographic orientation played a great role in the evolution of slip trace, lattice rotation and void growth.

On the other hand, the crack path of SC superalloy also shows distinct dependence on crystallographic orientation. Small fatigue cracks usually form and propagate along well-defined crystallographic planes in SC superalloy [2]. Due to different active slip systems, crack paths vary in small crack growth process for different orientations [18], and fracture surfaces are usually inclined to not only the loading direction but also the thickness direction [19]. Rough fracture surfaces give rise to crack closure and influence small fatigue crack propagation behavior.

Since crack-tip plasticity and roughness of fracture surfaces, which are the critical causes for crack closure, both show dependence on crystallographic orientation, effects of crystallographic orientation, especially secondary orientation on crack closure behaviors is an important subject while relevant experimental studies by in-situ SEM do not exist to our knowledge.

In this paper, crack closure behavior of small fatigue cracks in SC superalloy specimens for two different secondary orientations was studied based on in-situ SEM fatigue test. Different cracking modes were observed for two orientations. The measurements of CTOD were made and a model was developed to take into account the anisotropy of SC superalloy and analyze crack closure behavior. Effects of the secondary orientation on crack closure behaviors were revealed and their influences on fatigue crack growth rate were also discussed.

2. Material and experimental procedure

The material used here was a nickel-based SC superalloy and developed for fabricating hot sections of gas turbines. It was chemically analysed by energy dispersive spectrometer (EDS) and the nominal composition of this SC superalloy was given in Table 1. More information about the material was given in Ref. [14]. The specimens were fabricated by electrical discharge machining as a dog-bone-shaped sheet with a 0.6–0.8 mm-thick gauge section and a U-shaped edge notch at the center of the gauge section (Fig. 1). The specimens were all loaded parallel to the primary orientation [0 0 1] of the SC superalloy. Two different secondary orientations, i.e. crack growth directions, were chosen, which were [0 1 0] and [1 1 0] (Fig. 2). The octahedral slip planes in two specimens were shown in Fig. 2.

In order to reveal the microstructure, the polished surfaces of the specimens were etched in an aqueous solution of 4 g $CuSO_4$ + 20 mL HCl + 20 mL H_2O prior to fatigue test. The fatigue tests were conducted at 600 °C in the vacuum chamber of the SEM. In order to get a stable control of temperature along the gauge length, resistance coils with adjustable thermocouples were used and the control accuracies of temperature were about ±1 °C. The fatigue tests were load controlled under a maximal stress of 400 MPa and stress ratio of $R = 0.1$ at 10 Hz using a specially designed servo-hydraulic testing system.

According to Bowman et al. [4], crack closure measurements are very sensitive to alignment. Therefore, we have conducted a test to check the alignment of the test machine before the fatigue tests. The specimen is loaded while the applied load increases from 100 N to 700 N gradually. The notch opening displacements are measured according to the SEM images. The results (Fig. 3) show that the experiment system can produce linear load displacement curves.

Table 1
The nominal composition of the SC superalloy (wt.%).

Elements	Cr	Co	Mo	Al	Ti	Ta	W	C	Ni
Contents	12.2	9.0	1.9	3.6	4.1	5.0	3.8	0.07	Others

In order to observe the crack propagation and closure behaviors, the fatigue tests were paused at different loading cycles to capture the SEM images of small fatigue cracks and hence the fatigue crack growth rate (FCGR) can be calculated from the measured crack lengths [6,20,21]. A few more cycles were conducted manually after the system was halted and the position of the crack tip was determined. Afterwards, the specimen was unloaded from the maximum stress to 10% lower stress levels in sequence until the minimum stress. At each stress level, digital micrographs of the crack tip were taken so as to measure CTOD.

3. Experimental results

3.1. In-situ observation of small fatigue crack propagation

Fig. 4 shows the typical process of crack propagation of specimen [0 0 1]/[0 1 0]. The crack initiated from the notch root, and propagated along one single octahedral slip plane, which was 45° inclined to the loading direction on the observation surface (Fig. 4(a)). The crack propagated about 100 μm and then two sets of slip traces were evident ahead of the crack tip, which showed that the crack turned from one dominant slip plane cracking manner to two intersecting slip planes cracking manner when the crack was long enough (Fig. 4(b)). Afterwards, the crack propagated along two sets of slip planes alternately, resulting in the zigzag cracking mode (Fig. 4(c–e)). When the crack propagated about 600 μm, it turned to one dominant slip plane cracking manner again and began fast cracking until final fracture (Fig. 4(f)).

Different from specimen [0 0 1]/[0 1 0], specimen [0 0 1]/[1 1 0] shows straight cracking manner (Fig. 5). The crack began to propagate along a straight line which was parallel to the notch direction on the observation surface, ever since it initiated from the notch root (Fig. 5(a)). When the crack came across carbide inclusions, path deflection occurred (Fig. 5(d)). Generally, the crack propagated along a single dominant slip plane during the whole life.

3.2. In-situ observation of crack closure behavior

In-situ SEM observations of the crack closure behavior for the small fatigue cracks with a length of about 370 μm are shown in Figs. 6 and 7. In Fig. 6, the specimen [0 0 1]/[0 1 0] was unloaded from the maximum stress to the minimum stress (i.e. the minimum load is 10% of the maximum load for stress ratio $R = 0.1$). During the unloading process, some of the crack surface contacted at the stress level above 0.6 σ_{max} (Fig. 6(c)) due to the zigzag cracking manner, and the small crack was fully closed when the stress level was higher than 0.2 σ_{max} (Fig. 6(e)). For specimen [0 0 1]/[1 1 0], some of the crack surface contacted at the stress level above 0.5 σ_{max} (Fig. 7(c)), and the crack was fully closed when the stress level was higher than 0.1 σ_{max} (Fig. 7(e)).

3.3. Fractography analysis

SEM fractographic observations are shown in Figs. 8 and 9. Lerch's work [22] showed a method to predict the crack surface morphology which is shown in Fig. 2. For specimen [0 0 1]/[0 1 0] (Fig. 8), two conjugate fracture surfaces, i.e. slip planes $(\bar{1}\,1\,1)$ and $(\bar{1}\,1\,\bar{1})$, intersect with the intersection line along orientation $[0\,\bar{1}\,\bar{1}]$, which is 45° inclined to the loading direction. Fracture steps can be seen clearly on both fracture surfaces, indicating crystallographic fatigue failure mode. The typical γ/γ' microstructures of