International Journal of Fatigue 38 (2012) 36–45

Contents lists available at SciVerse ScienceDirect

International Journal of Fatigue

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

Stress ratio effects on small fatigue crack growth in Ti–6Al–4V

M.J. Caton [a,*], R. John [a], W.J. Porter [b], M.E. Burba [c]

[a] Materials and Manufacturing Directorate, Air Force Research Laboratory (AFRL/RXLMN), Wright-Patterson AFB, OH 45433-7817, USA
[b] University of Dayton Research Institute, Dayton, OH 45469-0020, USA
[c] Central State University, Wilberforce, OH 45384, USA

ARTICLE INFO

Article history:
Received 9 November 2008
Received in revised form 17 November 2011
Accepted 18 November 2011
Available online 25 November 2011

Keywords:
Fatigue
Small crack
Stress ratio
Titanium
Propagation

ABSTRACT

A systematic study of the effects of stress ratio on small fatigue crack growth in Ti–6Al–4V was conducted. Cylindrical fatigue specimens were tested axially at room temperature under a maximum stress of 690 MPa and with stress ratios (R) of 0.5, 0.1, and -1. Tests were periodically interrupted and a standard replication technique was used to monitor the growth of cracks artificially initiated from 30 to 40 μm micro-notches, which were milled into the specimen surface with a focused ion beam (FIB). Measurement of striation spacing from fracture surfaces was evaluated for determining small crack growth rates and showed good agreement with replication data, but is only possible for relatively high stress intensity factor ranges, ΔK, on the order of 10 MPa$\sqrt{m}$ or greater. A significant small crack effect is observed in this alloy, consistent with previous observations, where small cracks grew at stress intensity factor ranges below the long crack threshold and at higher rates than long cracks for equivalent ΔK levels. While a modest effect of stress ratio is seen on small crack growth rates when plotted as a function of crack size (faster growth at lower mean stresses for a given maximum stress), no discernable effect of R is seen when plotting as a function of ΔK. Significant scatter is observed in the small crack growth rates, and the implications of data reduction methods are discussed.

Published by Elsevier Ltd.

1. Introduction

Turbine engine components can be subjected to variable amplitude loading sufficient to initiate and propagate fatigue cracks and ultimately cause catastrophic failure. One application of particular interest is the *high cycle fatigue* (HCF) loading of fan and compressor airfoils that occurs during brief sweeps through resonant modes during throttle transients [1]. During these brief resonant excitations, isolated regions of an airfoil will experience a surge of progressively increasing then decreasing stress amplitude, where the stress ratio (R) is continuously changing (except for the case where $R = -1$). In determining safe-life limits for components and in developing real-time prognosis systems [2], it is necessary to understand the effect of stress ratio on fatigue crack propagation. In addition, it has been well established that small fatigue crack growth behavior is often poorly represented by traditional long crack data [3] and frequently demonstrates significantly greater variability than long cracks [4]. Therefore, it is critical that the influence of stress ratio on early crack growth behavior is understood, when crack sizes range from the order of microstructural initiating features up to roughly 1 mm. This paper examines the behavior of small cracks under different stress ratios in Ti–6Al–4V, an alloy commonly used for fan airfoils.

The effect of stress ratio on the long crack behavior in Ti–6Al–4V has been studied quite thoroughly [5–7], much of the work resulting from the Air Force-sponsored *High Cycle Fatigue* initiative [8]. In general, it is observed that crack growth rates for a given stress intensity factor range (ΔK) increase with increasing stress ratio, and crack growth thresholds (ΔK_{th}) decreases with increasing stress ratio. Below a critical stress ratio, R_c, crack closure is seen to be a dominant mechanism controlling the effect of R on crack growth rate. R_c for Ti–6Al–4V is roughly 0.5 [5]. Roughness-induced crack closure (RICC) is reported to be of particular importance in Ti–6Al–4V [7,9]. For stress ratios greater than R_c, where crack closure is considered negligible, Boyce and Ritchie [5] have shown that ΔK_{th} continues to decrease with increasing R and suggest that the K_{max} effect on the intrinsic crack growth mechanism controls this dependence.

Since small fatigue cracks are often considered to experience negligible levels of crack closure compared to long cracks, and closure is thought to be a dominant source of the observed R effect in long crack data, it might be reasonable to assume that small cracks will not demonstrate a significant dependence on R. However, a significant effect of R on small crack growth rates has been reported for aluminum alloys. Caton [10] observed a substantial effect of R on small cracks in a cast 319 aluminum alloy, where small cracks at $R = 0.1$ grew an order of magnitude faster than those at

* Corresponding author.
E-mail address: michael.caton@wpafb.af.mil (M.J. Caton).

0142-1123/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.ijfatigue.2011.11.004

$R = 0.5$, and an order of magnitude slower than those at $R = -1$. Additionally, Newman and Edwards [11] reported a strong stress level effect on the small crack growth rates in a 2024-T3 aluminum alloy that depended upon stress ratio. The stress level effect was most pronounced for negative R values, smaller for $R = 0$, and no stress level effect was observed at positive R values. While the mechanisms responsible for these observations are not fully understood, it is clearly important to identify the degree to which small crack behavior is influenced by R in order to accurately predict fatigue life under variable amplitude loading applications.

There have been numerous studies of small fatigue crack growth in Ti–6Al–4V [8,12–15], where several stress ratios have been examined. Fig. 1 shows a compilation of these data sets. Included in Fig. 1 are long crack growth curves, which were tabulated from a series of data generated under the HCF initiative [16]. The influence of stress ratio on the long crack growth is consistent with that described above. Higher applied R results in faster crack growth rates and lower ΔK_{th}, and the effect is less pronounced at higher R values (0.5 versus 0.8), where the contribution of crack closure is greatly diminished. The small crack data in Fig. 1 indicate a significant amount of scatter in behavior and provide clear evidence of a small crack effect in this alloy. That is, small cracks are observed to grow at ΔK levels below the long crack threshold (ΔK_{th}) and at faster rates than that of long cracks for a given ΔK. Within the small crack data provided in Fig. 1, which were acquired at stress ratios ranging from -1 to 0.5, it is difficult to discern any clear influence of stress ratio. However, it is important to note that the individual sets of small crack data were acquired under disparate testing conditions and for slightly different Ti–6Al–4V alloys; therefore direct comparison of these data is somewhat tenuous. Table 1 summarizes some of the key details of these tests and indicates where differences exist that could influence the crack growth behavior and render direct comparisons for different stress ratios inappropriate. While it is quite possible that stress ratio will have little influence on small crack growth in this alloy at room temperature, it is difficult to conclusively deduce this fact strictly from the data available in the literature.

This study is aimed at conducting a systematic examination of the effect of stress ratio on small fatigue crack growth rates in a controlled microstructure of Ti–6Al–4V [8]. In addition, the degree of variability observed in small crack behavior is evaluated and the sensitivity to different data reduction methods is explored. Determination of small crack growth rates based upon the measurement of striation spacing from fracture surfaces is evaluated similar to the work of Lenets and Bellows [15]. Growth rates from striation spacing shows good agreement with replication data, but is only applicable for relatively high stress intensity factor ranges where ΔK is on the order of 10 MPa$\sqrt{m}$ or greater.

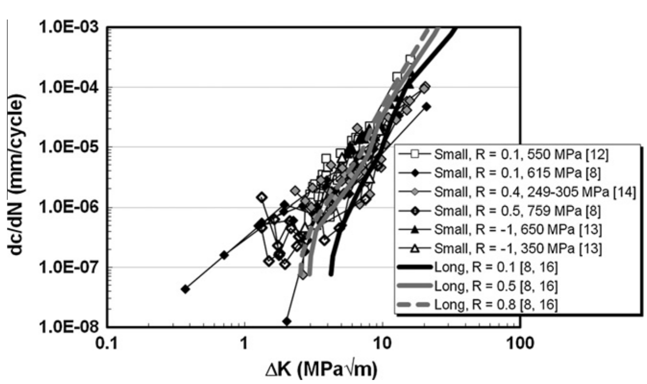

Fig. 1. A compilation of long and small fatigue crack growth data in Ti–6Al–4V acquired at several stress ratios and reported by numerous researchers [8,12–14,16].

2. Experimental procedures

The material investigated in this study is a Ti–6Al–4V alloy in a solution-treated and over-aged (STOA) condition. The specimens tested were taken from the same lot of material used in the Air Force-sponsored *High Cycle Fatigue* initiative [8], which included numerous industry, university, and government researchers. The microstructure, shown in Fig. 2, consists of 60-vol% equiaxed primary alpha phase with an average grain size of 20 μm and 40-vol% transformed beta phase. The alloy demonstrates average yield strength of 930 MPa and ultimate tensile strength of 978 MPa at room temperature. Fig. 2a shows that the grain structure is quite equiaxed and uniform, and Fig. 2b provides an alpha grain size distribution acquired through orientation image mapping (OIM) software. It is seen that the average alpha grain size is roughly 10 μm.

The dimensions of the smooth, cylindrical specimen used to monitor small fatigue crack growth are shown in Fig. 3. The gage section is 20.6 mm long and has a diameter of 4.2 mm. Micro-notches were milled into the specimens using a focused ion beam (FIB) in order to artificially initiate fatigue cracks. Each specimen contained 9 micro-notches and Fig. 4 shows that they were placed an adequate distance from each other in order to minimize crack interaction effects. Fig. 5 shows an example of a micro-notch as seen both on the specimen surface and on the fracture surface. All micro-notches had a depth to surface length ratio of 1:2, and a height to surface length ratio of roughly 1:10. The surface lengths of the micro-notches used are outlined in Table 2, and were roughly 30 μm or 40 μm depending on the testing condition. Nine micro-notches were chosen to enable the acquisition of a significant amount of small crack data from a single test and to evaluate the variability observed in crack growth behavior due to the variation in microstructure within a specimen.

Small crack growth was monitored using a standard replication technique with cellulose acetate tape. Fatigue cycling was periodically interrupted, and replicas were taken while placing the specimen under a tensile hold load of 60% σ_{max}. All tests were conducted using a servo-hydraulic test frame under load-control at room temperature in lab air and at a frequency of 20 Hz. Four specimens were tested in total. Three specimens were tested at a maximum stress of 690 MPa with stress ratios of -1, 0.1, and 0.5, respectively. Additionally, one specimen was tested at a stress ratio of 0.1 with a maximum stress of 620 MPa. Subsequent to failure, the fracture surface of each specimen was examined with scanning electron microscopy (SEM). For each specimen tested at 690 MPa, fatigue striations were found and the average striation spacing was measured for numerous crack sizes using an image analysis software package.

3. Results and discussion

3.1. Crack initiation

While each fatigue specimen contained 9 micro-notches, a crack did not necessarily initiate from every micro-notch. Table 2 summarizes the observations of crack initiation in each of the specimens. Most of the micro-notches were 30 μm in surface length, however, 6 of the 9 micro-notches in the specimen tested at $R = 0.5$ were made somewhat larger (40 μm) since it was expected that initiating a crack would be more challenging under these loading conditions. Included in Table 2 are initial stress intensity ranges, ΔK, calculated using the solution from Raju and Newman [17] for a surface crack in a rod. These calculations assume that the micro-notches are semi-circular cracks ($a = c$) like that depicted in Fig. 4. It is recognized that this assumption simplifies the true stress intensity factor at the micro-notch tips; however, these values provide a very reasonable