DETERMINING LOAD HISTORY EFFECTS ON HCF CRACK GROWTH THRESHOLDS

Monty A. Moshier[1], Theodore Nicholas[2], and Ben M. Hillberry[3]

[1]Anteon Corporation, Dayton, OH 45431
[2]Air Force Research Laboratory, Materials and Manufacturing Directorate (AFRL/MLLM) Wright-Patterson AFB, OH 45433-7817.
[3]Purdue University, School of Mechanical Engineering, West Lafayette, IN 47907.

ABSTRACT

The effect of load history on the fatigue crack growth threshold in Ti-6Al-4V at room temperature was evaluated using two specimen configurations. Short crack tests were conducted on notched specimens under load control to produce low cycle fatigue surface precracks in the size range 25 µm – 600 µm at R=0.1 and R=-1. The threshold for high cycle fatigue (HCF) crack propagation was then determined at 600 Hz using a step loading procedure. Long crack tests were conducted on C(T) specimens by subjecting them to constant high ΔK controlled prior cracking at R=0.1 and then determining the threshold using a procedure comprising an increasing ΔK, constant R, step-load method. In both test types, stress-relief annealing (SRA) is applied to some of the specimens after the load history has been applied but before the threshold determination. While the load history is seen to effect the subsequent threshold in the form of an underload or overload effect, results show that SRA removes all load history effects and produces a true material threshold which is independent of the load history. This true threshold is found to be slightly lower than the value obtained using C(T) specimens and standard load shed techniques.

KEY WORDS

High cycle fatigue, Load history effects, Small cracks, Overloads, Threshold

INTRODUCTION

Many HCF failures in gas turbine engines are the result of in-service damage due to fretting, foreign object damage (FOD), LCF, or others [1]. In the presence of damage and due to the large numbers of cycles applied in short periods of time the idea of a threshold below which HCF does not occur is necessary. Damage tolerance for HCF when initial cracks are present would therefore require the determination of a crack growth threshold applicable to the conditions under which the crack was formed. This study investigates the high cycle fatigue (HCF) threshold of a typical fan blade material, Ti-6Al-4V, when naturally initiated fatigue cracks, which have been created using different LCF loading sequences, are present.

EXPERIMENTS

All specimens were machined from forged Ti-6Al-4V plate. The titanium alloy had an alpha-beta microstructure of approximately 60% primary alpha with the remainder transformed beta. The mechanical properties of the Ti-6Al-4V plate are σ_y = 930 MPa and σ_{UTS} = 980 MPa.

Small Crack Testing

Double notch tension test specimens were stress relieved after machining and then electro-polished in the gage section in the vicinity of the notches. The two notches had the same depth but different notch root radii, thereby producing almost no bending when applying fixed grip axial loading. The notch geometries were chosen so that failure could be confined to the more severe notch having an elastic stress concentration factor, K_t, of 2.2.

LCF was conducted at stress ratios of –1.0 and 0.1 under load control to initiate a crack using a sinusoidal wave form at a frequency of 10 Hz with a superimposed hold time of 0.5 s on each cycle during which the DCPD measurements could be made. Maximum stress levels (430 MPa at R=0.1 and 265 MPa at R=-1.0) were chosen which corresponded to approximately 250,000 cycles to failure. Cracks were typically detected with DCPD at cycle counts between 20,000 and 100,000 at which point the tests were stopped and the specimens inspected in the SEM to confirm the existence of a crack.

To fully characterize the geometry of these cracks in order to determine ΔK_{th}, the crack shape was determined by heat tinting the LCF cracked specimens at 400°C for four hours prior to HCF threshold testing. Heat tinting marks the crack profile for post fracture measurement of the crack geometry without affecting any subsequent crack growth properties.

The LCF cracked specimens were then tested in HCF using a step loading procedure to determine the failure stress [2]. The tests were conducted in a custom built HCF apparatus at a frequency of 600 Hz. The thresholds in the form of values of ΔK were determined from the load for crack extension to occur, and from the measurements of the initial crack size using heat tinting. K values were determined using the finite element method to modify existing solutions developed for a semi-elliptical surface crack and corner crack in a single edged notch tension specimen. In this work, ΔK_{th} is defined as the value of ΔK where propagation begins from a no-growth state. It was interpolated using the average of the load where no crack extension occurred and the load at which crack extension was observed. From the crack measurements made from the fracture surfaces, the interpolated threshold stress and the modified stress intensity factor solution, a value of ΔK_{th} was determined which represents the onset of crack propagation.

Long Crack Testing

Threshold testing was conducted on C(T) specimens under K-controlled conditions using a sinusoidal waveform at a frequency of 50 Hz using a step load procedure similar to that used in the HCF testing [2] in order to determine at what K level crack extension occurs. The method involves subjecting a specimen to 200,000 cycles at a K level below which crack extension was anticipated to occur. The 200,000 cycles was determined to be sufficiently large so that crack extension would be detected. If crack extension is not detected within the block of 200,000 cycles the level of K is increased 0.2 MPa√m and the test repeated until the crack extension occurs. The threshold is defined to be the average of the K levels where no crack extension occurs and where crack extension first occurs. Because the increments are 0.2 MPa√m, the error is at worst 0.1 MPa√m.

RESULTS AND DISCUSSION

Small Cracks

Cracks initiated under LCF were measured under load in a SEM to determine the surface crack length, 2a. The depth of the crack was determined from the fracture surface that showed the heat tinted pattern of the crack after LCF but before HCF. Figure 1 shows the linear fit of the “a” and “c” crack data. The values of “a” from the heat tinted surface, covering a range from 25 to 400 μm, were in general agreement with the surface crack measurements in the SEM.

One method for evaluating threshold crack growth data is to compare stresses for a given crack size against crack length for LCF generated cracks and data extrapolated from a long crack growth threshold test. Such information can be presented in the form of a Kitagawa diagram [4], which plots stress against crack size. Using logarithmic scales, a crack growth threshold for a geometry where K is proportional to √c (c is flaw size) produces a straight line of slope=-0.5 while the endurance limit of an uncracked material is a line of constant stress.

For any given geometry, all combinations of crack length and stress corresponding to a K solution equal to the threshold value establish the threshold crack growth line. This line now represents the fracture mechanics solution down to arbitrarily short crack lengths and makes no assumptions about the lack of validity of the solution for such short cracks. The short crack anomaly is easily demonstrated because the threshold value from the K solution produces stress levels for arbitrarily short cracks that are above the endurance limit yet below the crack growth threshold. Much more important is the concept of data points below the endurance limit and below the threshold ΔK for short cracks of a particular size. It is clear that such cracks could not be naturally initiated since they develop under stress levels that are below the endurance limit. It follows, therefore, that data plotted on a Kitagawa diagram representing a crack length and stress below the endurance limit generally represent a condition where the crack was initiated above the endurance limit. An alternate explanation might be that a complex stress field allows the initiation, but not propagation of a crack. In this case, the simple K solution that produces the line of constant K is no longer valid and the actual K solution has to be represented in the diagram. With this in mind, the question is raised as to whether any point on a Kitagawa diagram is unique or, instead, is dependent on the history of loading in getting to that point. The long crack threshold is clearly an example of a data point which is dependent on load shed history. While standards have been set for determining this threshold by following a predetermined history, the history dependence and the existence of a unique long crack threshold still have to be questioned.

The data for the HCF threshold after a LCF crack was initiated are plotted in a Kitagawa type diagram in Figure 2. In the figure, a line is drawn representing the long crack threshold of K_{max}=5.1 MPa√m for R=0.1. The line represents the stresses calculated from the long crack thresholds above and the linear fit from the a/c data (Fig. 1). The horizontal line represents the experimentally determined endurance limit for the notched specimens corresponding to 10^7 cycles. It can be seen that the data which were obtained using LCF at R=-1.0 (triangles) tend to fall slightly below the projected long crack threshold, the type of effect being representative of what one would expect when a material sees an underload during prior cycling. Conversely, the circles which represent data obtained under LCF at R=0.1 show what appears to be equivalent to an overload effect since the threshold values of stress are consistently above the long crack threshold.

Also shown are small solid circles and triangles which represent specimens which were cracked in LCF, stress relief annealed (SRA), and then tested in HCF. The small circles represent specimens which were cracked using the same stress level as the larger circles (R=0.1) while the small triangles represent specimens which were cracked at the same level as the larger triangles (R=-1.0). The data indicate that the stress relief annealing process, which eliminates residual stresses, provides a baseline threshold level for different crack lengths, independent of load history.

Long Cracks

Long crack threshold testing was conducted to determine the effect of different K_{max} prior history on the measured long crack thresholds. The range of K_{max} used for precracking was 6 to 25 MPa√m. The resulting measured K_{max} thresholds, covering the range 4.6 to 11.2 MPa√m, vary linearly with the K_{max} used for the precrack (Fig. 3). Additionally, identical tests were conducted on specimens subjected to SRA. The long crack K_{max} threshold measurements for these specimens were 4.5 to 4.9 MPa√m for R=0.1 regardless of the prior ΔK level. These data provide a nearly constant estimate of the threshold that is slightly lower and more conservative than the long crack threshold, measured by standard load shed techniques, of 5.1 MPa√m. Similar experiments were conducted at R=0.5. The results are shown in Fig. 3 where the SRA threshold is 5.6 MPa√m, which is only slightly lower than the long crack threshold, from standard load shedding, of 5.8 MPa√m

Small Crack / Long Crack Threshold

The short crack threshold data from the DE(T)specimens can be plotted in the same format as the long crack data using the final crack length and stress amplitude necessary to initiate the cracks to calculate the K_{max} precrack. The K_{max} precrack ranged from 3.6 to 24.7 MPa√m and the measured K_{max} threshold ranged from 4.1 to 10.8 MPa√m. The small crack data (the open circles and open triangles in Fig. 4) appear to follow the same trend as the long crack data for the HCF thresholds produced at R=0.1. The SRA short crack specimen data (filled circles and triangles) produce thresholds that are near the measured SRA long crack thresholds. The K_{max} thresholds for the small cracks appear to be independent of the crack lengths that are related to the K_{max} of the precrack. The crack sizes of the small crack threshold data (Fig. 4) correspond to the data shown on the Kitagawa diagram (Fig. 2). The smaller cracks have lower K_{max} precracks due to the constant maximum applied stress (430 MPa at R=0.1 and 265 MPa at R=-1.0) that was used for the LCF crack initiation. It is important to note that because of this, the plastic zone sizes for the small crack data are much smaller than the cracks. It is also important to mention that the LCF R=-1.0 HCF threshold data (open triangles in Fig. 4) follow the same trend as the SRA HCF threshold data, indicating that R=-1.0 appears to be an appropriate stress ratio for initiating small cracks without loading histories. It is speculated that the compression portion of the R=-1.0 loading may remove closure effects, similar to what occurs when periodic underloads are applied.

CONCLUSIONS

Threshold values obtained on notched short crack specimens which are precracked in LCF at R=0.1 and R=-1.0 show a definite load history effect. LCF conducted at R=0.1 prior to HCF produces an overload effect which, in turn, increases the subsequent HCF threshold. On the other hand, LCF at R=-1.0 produces a slightly lower threshold than that from standard load shedding.

These results, when plotted in the form of a Kitagawa diagram, indicate that values of crack growth threshold are not unique but instead depend on the loading history used to produce the cracks. The small crack threshold data collected by initiating cracks in LCF and subsequent SRA and the threshold data collected by first initiating cracks in LCF at R=-1.0 appear to follow the same trend. These data are below the long crack load shed threshold on the Kitagawa diagram, indicating that load history free small crack data can be collected by either initiating at R=-1.0 or using SRA.

Load-history free threshold measurements in the C(T) specimen can be made by first precracking the specimen with subsequent SRA and threshold testing. In addition to the measurements being load history free, many tests can be completed with one specimen resulting in a significant time savings when the stress relief annealed step test is used.

REFERENCES

[1] Nicholas, T. and Zuiker, J.R., "On the Use of the Goodman Diagram for High Cycle Fatigue Design," *International Journal of Fracture*, **80**, 1996, pp. 219-235.

[2] Maxwell, D.C. and Nicholas, T., "A Rapid Method for Generation of a Haigh Diagram for High Cycle Fatigue," *Fatigue and Fracture Mechanics: 29th Volume*, *ASTM STP 1321*, T.L. Panontin and S.D. Sheppard, Eds., American Society for Testing and Materials, West Conshohocken, PA, 1999, pp. 626-641.

[3] Frost, N.E., "Notch Effects and the Critical Alternating Stress Required to Propagate a Crack in an Aluminum Alloy Subject to Fatigue Loading," *J. Mech. Eng. Sci*., **2**, 1960, pp. 109-119**.**

[4] Kitagawa, H. and Takahashi, S., "Applicability of Fracture Mechanics to Very Small Cracks or the Cracks in the Early Stage," *Proc. of Second International Conference on Mechanical Behaviour of Materials*, Boston, MA, 1976, pp. 627-631.

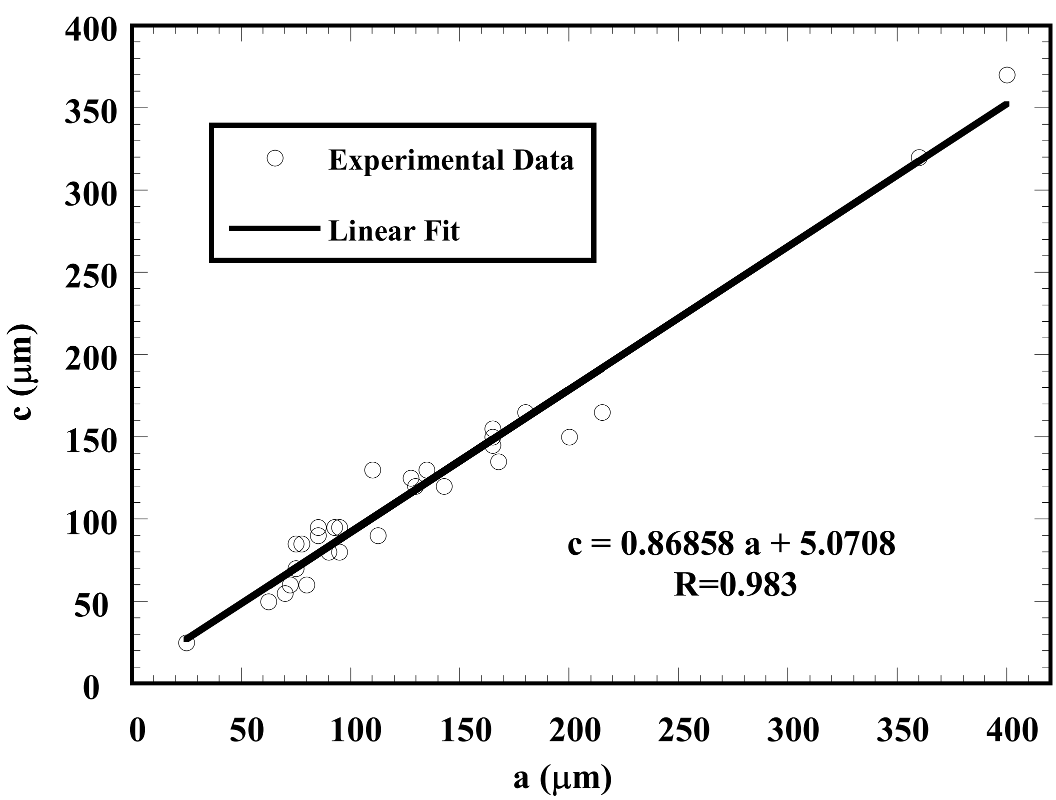

Figure 1 Experimental results for measured crack geometries.

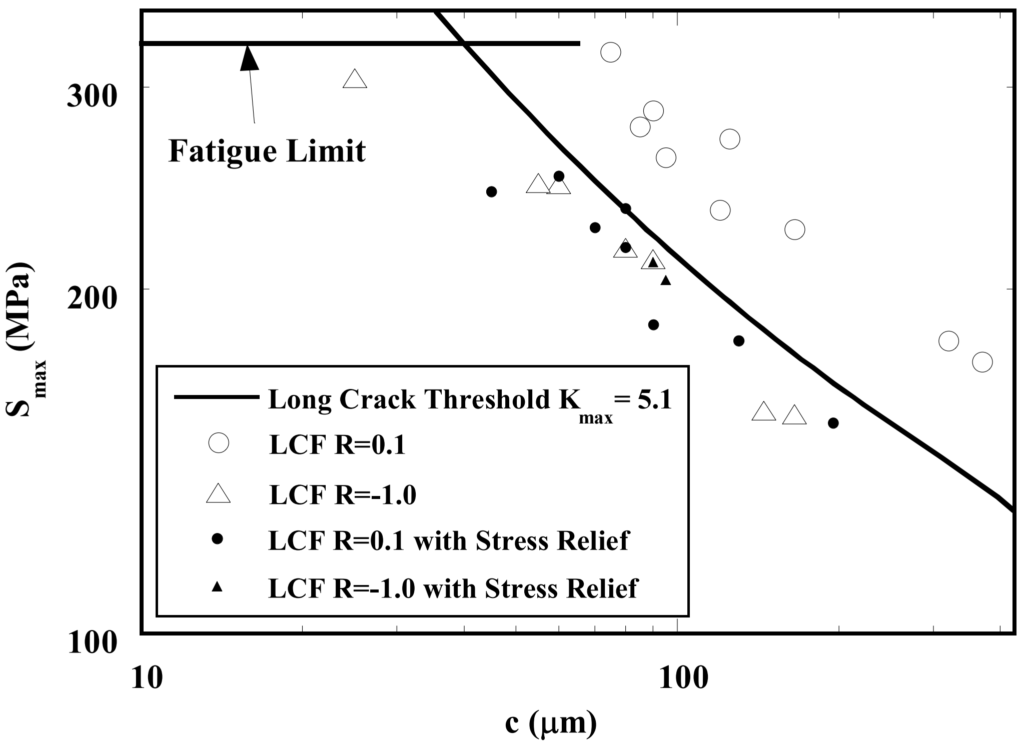

Figure 2 HCF thresholds at R=0.1 on a Kitagawa type diagram plotted versus “c”.

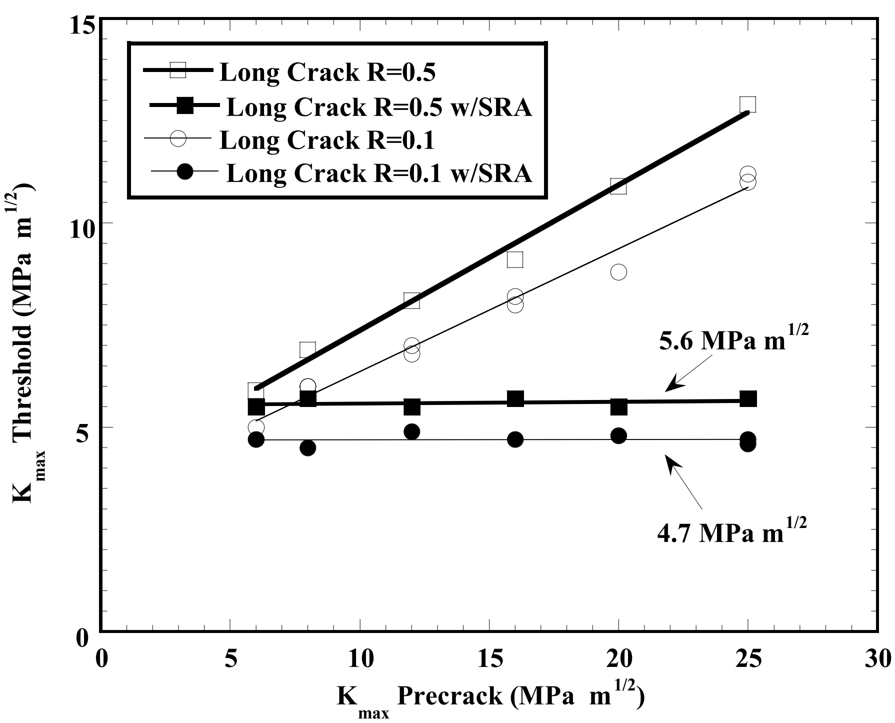

Figure 3 Long crack threshold data R=0.1 and R=0.5.

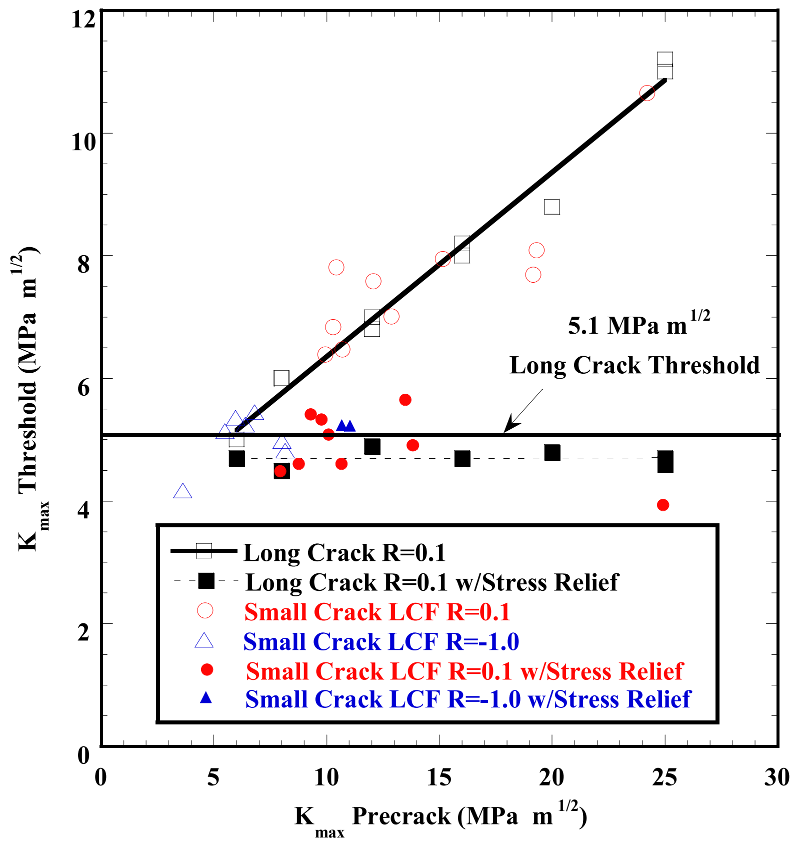

Figure 4 Long and small crack threshold data trends R=0.1.