Fatigue Crack Growth Behavior in the Threshold Region

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Abstract. This paper describes the results of a research program conducted to improve the understanding of fatigue crack growth rate behavior in the threshold growth rate region and to answer a question on the validity of threshold region test data. The validity question relates to the view held by some experimentalists that using the ASTM load shedding test method does not produce valid threshold test results and material properties. The question involves the fanning behavior observed in threshold region of da/dN plots for some materials in which the low R-ratio data fans out from the high R-ratio data. This fanning behavior or elevation of threshold values in the low R-ratio tests is generally assumed to be caused by an increase in crack closure in the low R-ratio tests. Also, the increase in crack closure is assumed by some experimentalists to result from using the ASTM load shedding test procedure. The belief is that this procedure induces load history effects which cause remote closure from plasticity and/or roughness changes in the surface morphology. However, experimental studies performed by the authors have shown that the increase in crack closure is a result of extensive crack tip bifurcations that can occur in some materials, particularly in aluminum alloys, when the crack tip cyclic yield zone size becomes less than the grain size of the alloy. This behavior is related to the high stacking fault energy (SFE) property of aluminum alloys which results in easier slip characteristics. Therefore, the fanning behavior which occurs in aluminum alloys is a function of intrinsic dislocation property of the alloy, and therefore, the fanned data does represent the true threshold properties of the material. However, for the corrosion sensitive steel alloys tested in laboratory air, the occurrence of fanning results from fretting corrosion at the crack tips, and these results should not be considered to be representative of valid threshold properties because the fanning is eliminated when testing is performed in dry air.

Introduction

The initial concern at JSC over the validity of fatigue crack growth threshold data began during an involvement in a program initiated in 2003 by the Federal Aviation Administration (FAA) to improve damage tolerance analysis methods for rotorcraft and aircraft propeller systems. In this program an issue arose about the causes of fanning behavior and the validity of da/dN data generated in the threshold region by using the load shedding test method. Because the threshold properties of materials are very important in fracture control in NASA space programs, JSC initiated an in-house program to research the causes of fanning behavior. An initial literature survey revealed that the fanning behavior of steel alloys had already been investigated [1, 2] and the causes resolved. This early research determined that fanning of corrosion sensitive alloys will occur from fretting corrosion when cyclic loaded in semi humid air and would be eliminated by testing in argon environment. In the NASA JSC threshold test program, the fanning behavior seen for D6AC, AISI4340 and AerMet steels was prevented by testing in dry air. However, testing in dry air did not eliminate fanning in aluminum alloy tests. Also, published research experiments by Hertzberg [3, 4] showed that crack surface morphology (i.e. an increase in roughness) undergoes a change in the threshold region, and this could affect fanning. These cover the main investigations described in this paper.

Test Program

The primary specimen types used for this study were the compact and extended compact, C(T) and ESE(T), type specimens. A vast range of different material types was tested which included but not limited to AISI4340 steel, 2198, 2524, 6061, 6156 and 7075 aluminum alloys. All specimens

were machined in accordance with the ASTM E647 standard [5]. A single KRAK gage [6] was bonded on each specimen in order to acquire crack growth rate data during the fatigue cycling. The thin notch in each specimen was cut by an electron-discharge machine (EDM) using 0.254mm (0.010 inch) diameter wire.

Previous testing [2] had indicated that for some materials, such as 4340 and D6AC steels which are corrosion sensitive, that testing in 50% humidity laboratory air would result in fanning of the test data. For this reason, many specimens were tested in dry air. The dry air test environment was achieved by providing a continuous flow of dry shop air (<1% measured humidity) into a plastic bag that enclosed the specimens. A small hole in the bottom of the bag allowed the slow flow of shop air to escape while maintaining the positive air pressure in the bag.

Test specimens for each material were generally fatigue tested at three load ratios: R=0.1, 0.4, and 0.7. For each test, both for load shedding and increasing load phases, the constant R, K control test method was used to produce a wide range of da/dN data for each specimen.

Results and Discussions

In earlier electron microscope studies of threshold fatigue crack growth behavior (e.g., by Hertzberg), only the crack surface morphology was studied by taking replicas of the crack surfaces of specimens that were broken apart. Since this method did not provide an understanding of the effect of the surface morphology on crack closure, the method used in the JSC program was to perform scanning electron microscope (SEM) studies of the crack growth patterns on the faces of the specimens while the specimens were still intact, and mostly just after completion of the threshold test phase. This technique provided a much improved understanding of threshold crack growth behavior and the effect of the crack surface morphology on crack closure.

Effects of Crack Tightness and Material Yield Strength. In the SEM investigations by JSC, such as shown in the 500X photo in Fig. 1, the photo shows that the threshold region crack in the AISI4340 steel specimen tested in dry air is seen to be very tight and straight when compared with the threshold crack in the 6156-T6 aluminum specimen shown in Fig. 2. Since the fanning in 4340 steel dry air tests was insignificant compared to that of the aluminum specimen tests, this illustrates that when a load threshold crack is straight and tight with very limited forking, no fanning behavior occurs in the threshold data.

Since plastic wake effects are believed by some to be the cause of fanning, materials with low yield strengths should have the greatest amount of fanning. To investigate this assumption, AISI304 steel and 2198-T8 aluminum (with yield strength of 207MPa and 503MPa) specimens were also tested. The results of these tests are shown in Fig. 3. This finding confirms that the plastic wake does not play an influential role in the fanning behavior observed for the aluminum alloys tested, but that the microstructure characteristics of a material is most important.
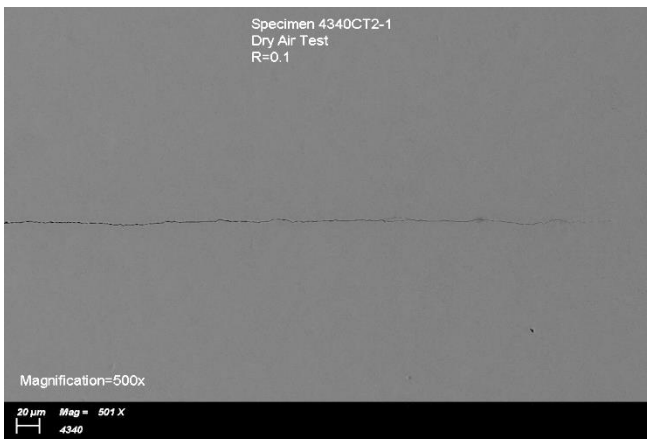

Fig. 1, Threshold region crack growth in a C(T) 4340 steel specimen tested at R=0.1 (501x mag).
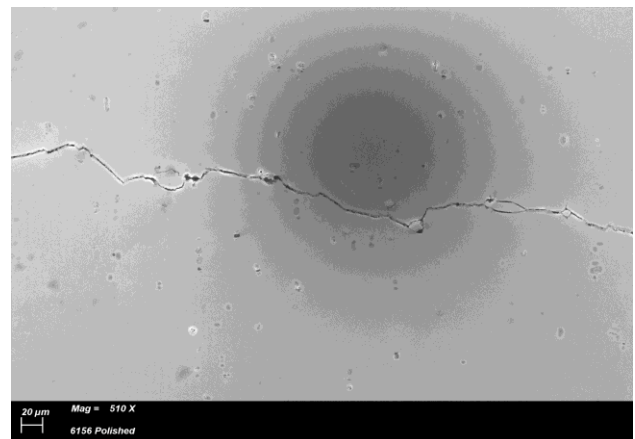
Fig. 2, Threshold region crack growth in an ESE(T) Al 6156-T6 specimen tested at R=0.1 (510x mag).
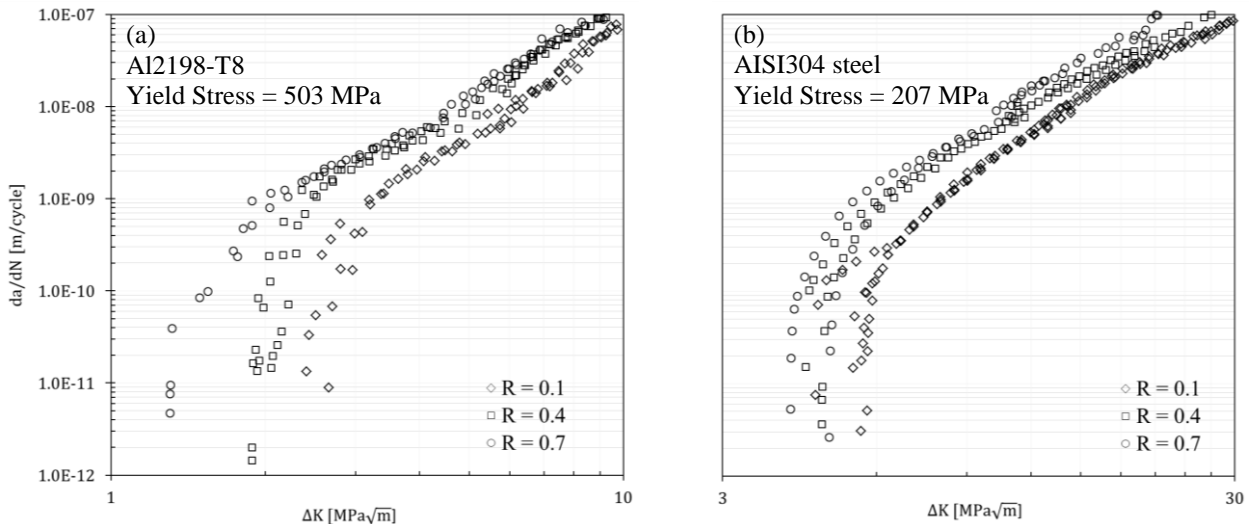
Fig. 3, ESE(T) specimen type FCGR data for (a) Al 2198-T8 in lab air with L-T grain orientation and (b) AISI304 steel in dry air with T-L grain orientation

Crack Closure From Internal Particles and Debris in Cracks. Another observation made for aluminum alloy specimens was the presence of debris particles that had broken loose from the crack surfaces. Upon investigation, certain specimens clearly had micro-bifurcations forming along the inside and outside area of the crack region, and in some cases these micro-bifurcations had led to small pieces of material breaking loose and being wedged in the crack. This occurrence was noted for both ΔK increasing and ΔK decreasing test types. Fig. 4 and Fig. 5 show an Al 7075-T7351 specimen for which this behavior was seen in a ΔK increasing test. The photograph of the specimen (Fig. 4) was taken at a point 2.4mm from the notch, which corresponds to an area of slow crack growth (<2.5e-8 m/cycle). This implies that micro-bifurcations and debris separation along a crack are independent of whether ΔK is decreasing or increasing, but rather depend on how slowly the crack propagates.
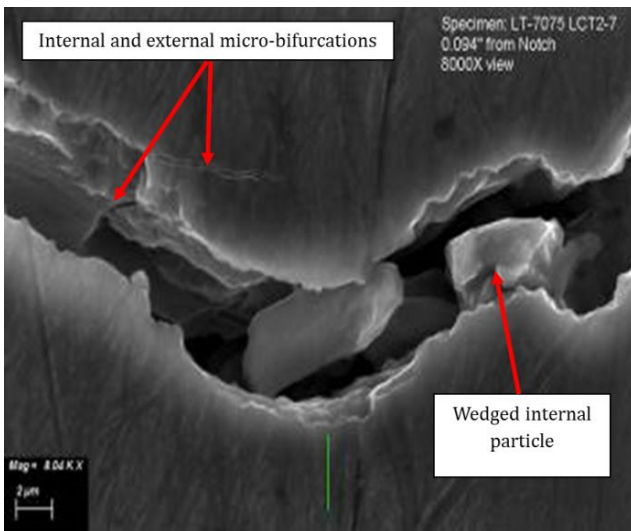

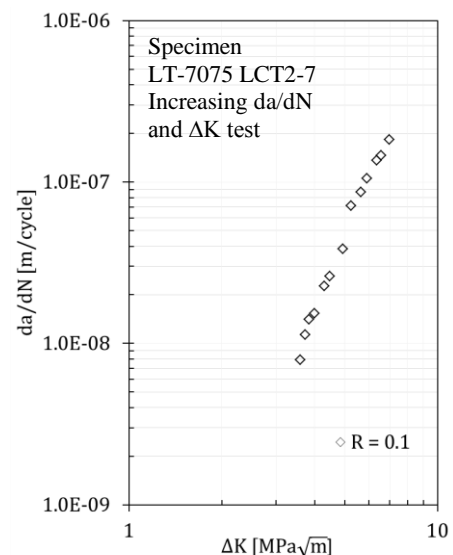Fig. 4. Al 7075-T7351 specimen showing micro-bifurcations and internal debris (8000x mag).

Fig. 5. FCGR data for Al 7075-T7351 specimen with micro-bifurcations and internal debris.

The fact that micro-bifurcations can be seen on the inner crack surface in Fig. 4 indicates that a number of debris particles may be present out of sight beyond the face of the crack. The number of particles generated by this type of fracture behavior can cause early crack closure and therefore cause significant fanning of data during fatigue crack growth testing. Wasén [7] also notes this

phenomenon and discusses the large number of experimental results that have indicated the effect on crack closure due to fracture surface roughness, debris, and oxide formation.

Threshold Region Crack Bifurcations and Sharp Turns in Aluminum Alloy Specimens. A general characteristic observed in each of the different aluminum alloys tested was that extensive crack bifurcation behavior and sharp 90 degree turns occurred for crack growth in the threshold region. This behavior is shown in Fig. 6 and Fig. 7 and would have obviously caused localized contact points that would alter crack closure. This general behavior did not occur for the steel specimens where the cracks were much straighter.

   For all the different alloys investigated in this threshold study effort, SEM views of the crack growth on the specimen surface showed that in the threshold region, a change to a highly rough growth behavior and, for all aluminum alloys, an extensive amount of crack branching was found to occur. In viewing the SEM photos in Fig. 6 and Fig. 7, it is obvious that increased crack closure occurs as a result of the crack bifurcation behavior. This increased closure can be described as geometric closure resulting from the occurrence of random high points of contact that can form on the crack surface when a crack bifurcates. This occurrence of crack branching in the threshold region was discussed by Hertzberg in his book [4].
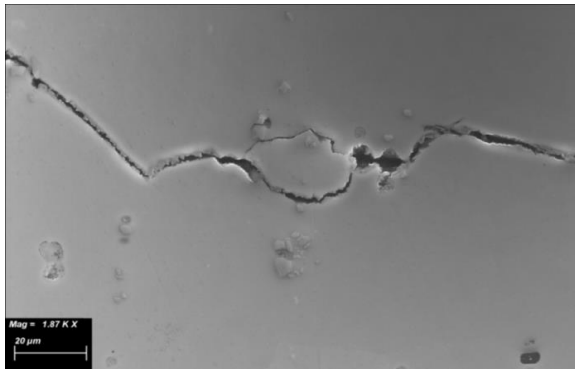

Fig. 6. Aluminum 6156 specimen showing sharp turns and particle separation (1870x mag).
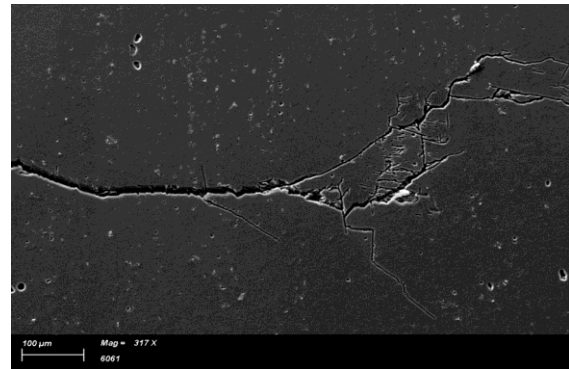
Fig. 7. Aluminum 6061 specimen threshold crack tip (317x mag).

Fatigue Crack Surface Morphologies. Hertzberg and Mills [3] published results of SEM studies performed on aluminum and steel fatigue crack growth specimens which showed that fatigue surface morphology can be separated into three distinct regions: (1) "faceted growth" or cleavage like in the ultra-low or threshold regime, (2) "striated growth" in the mid-growth rate regime where fatigue striations are observable and (3) "ductile growth" in the near fracture regime. Also, Hertzberg [4] discusses the transition point proposed by Yoder et al [8] where the striated region changes to the faceted region when the cyclic plastic yield zone at the crack tip becomes smaller than the material's grain size.

   This change in crack morphology was attributed by Hertzberg to the ranking of the stacking-fault energy (SFE) property of a material, with the change being greater for materials such as aluminum, which are reported to have high values of SFE. The SFE results are directly proportional to the mobility of dislocations and thus high value of SFE represents high mobility of dislocations.

   In the first SEM investigations of threshold test specimens performed at JSC, the studies quickly confirmed the change in crack surface morphology in the final threshold region of crack growth. The JSC results, shown in Fig. 8, also showed that the morphology change was dependent on the growth rate, and particularly when the crack tip yield zone size became less than the material grain size [8]. Also, the behavior was found to be the same at both R=0.1 and R=0.7 fatigue stress ratios. Since the fanning is highest for low R-ratio test data and the surface morphology is the same for both ratios, this confirms that the fanning is principally a function of the crack surface morphology and thus a function of the difference in closure between R=0.1 and R=0.7 load ratios.

Other Effects of Crack Bifurcation Behavior. In addition to causing fanning of the threshold data at low R-values, the crack bifurcation behavior was found to have been the cause of a problem in

the subsequent ΔK increasing test phase for some materials. For materials that showed significant fanning at threshold, when the ΔK increasing tests were run, the growth rate decreased for some distance of crack growth before the growth rate began to increase.

Fig. 9 shows this initial decrease in crack growth for a Pyrowear C(T) specimen that was tested in lab air. This caused the da/dN data to be invalid for a major portion of the increasing ΔK test phase. After understanding the cause of the problem, later tests procedures were changed to eliminate the problem. This was accomplished by extending the initial machined notch in a specimen by sawing about 1.27mm past the threshold crack tip with a 0.3mm thick razor saw. This worked very well because the simple straight notches were cut by 0.254mm diameter EDM wire
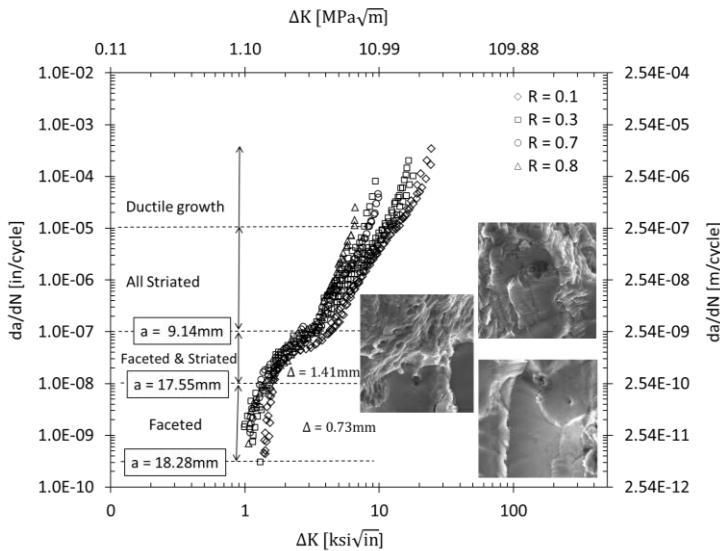

Fig. 8, Morphology transition for different crack growth rate regions in a 7050-T7451 aluminum specimen.
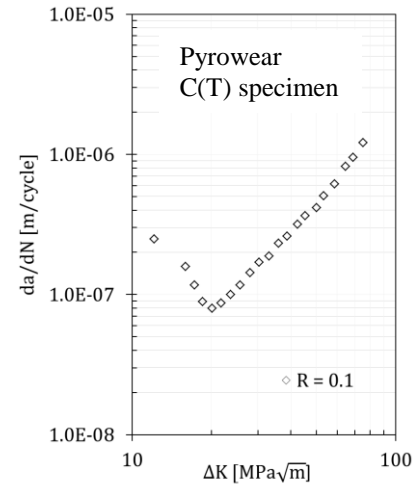
Fig. 9, Initial decrease in crack growth rate for an increasing ΔK test.

From studying SEM photographs of fatigue crack growth in the threshold region for a number of metal alloys, it is clear that conventional solid mechanics theory does not predict the observed crack growth behavior. Conventional elastic-plastic fracture mechanics analysis does not predict the observed tendencies of crack branching, changes in crack surface micro-morphology and arbitrary, non-ductile directions of crack growth paths that affect crack closure behavior and the resulting fanning of the threshold region data for certain, but not all, tested materials.

In reviewing numerous published metallurgical studies covering these characteristics of fatigue crack growth, it is obvious that the growth behavior is more likely governed by the dislocation theory of metals where the crack growth is influenced by material characteristics such as crystal structure, slip characteristics, and dislocation density or stacking fault energy (SFE) properties. Numerous technical papers and books have been published which discuss aspects of how dislocation theory relates to crack propagation in metal alloys. Readers are referred to references [3,4,9] for further details.

Summary of Discussion

In summary, the present studies indicate that fanning in the threshold regime is likely a result of other factors than a plastic wake developed during load shedding. The cause of fanning at low R-values is primarily a result of a localized roughness introduced by crack bifurcations and oxide build-ups, which alter the crack closure at low R-values. As pointed out by Hertzberg, all of the many materials he examined showed a transition in the crack surface morphology when entering the threshold region from smooth striated surfaces to rougher faceted surfaces. However, of the many materials investigated by JSC, only the aluminum alloys exhibited the severe bifurcation behavior and along with it the major fanning behavior at low R cyclic stress ratios. Furthermore, the aluminum alloys had an order of magnitude higher level of SFE compared to the other alloys (e.g., 250 mJ/m2 for aluminum and <10 mJ/m2 for iron based materials). Thus, this confirms the importance of SFE in threshold crack surface morphology as stated by Hertzberg. The conclusion

can therefore be made that crack growth behavior in the threshold regime involves both crack closure theory and the dislocation theory of metals.

In essence, the change in crack morphology at threshold is a function of an inherent material property. When such is the case, and crack morphology changes are not environmentally caused, higher thresholds are valid material values and should be allowed for use in crack growth life analysis.

Conclusions

1) An extensive amount of full-range da/dN vs ΔK test data was generated for a number of aluminum, steel and titanium alloys that are important for conducting damage tolerance analysis on rotor craft and aircraft propeller systems. 2) An important improvement was made and a problem resolved in using the ASTM test procedure for generating full-range da/dN vs ΔK data from a single specimen when the ΔK increasing data is not continuous with the threshold load shedding data. 3) The testing confirmed earlier published test results in which fanning of da/dN data at low load ratio (R) values in the Stage I threshold region for iron based steel alloys is caused by a buildup of iron oxide on the crack surfaces from fretting corrosion, and the fanning can be reduced by testing in dry air. 4) It was determined that the fanning behavior for aluminum alloys is caused by crack bifurcation behavior which results from the crystal or microstructure of these alloys and possibly by their inherent high level of stacking fault energy properties. When fanning of da/dN data in the threshold region is caused by the inherent microstructure of the material, the threshold data should be considered as valid data and not as being caused by the ASTM load shedding test method. 5) It is also apparent that the correlation between stacking fault energy and crack bifurcation is insufficiently defined by current studies. Stacking fault energy has been said to have an effect on dislocation mobility within a material; however, the way in which this effect may cause bifurcations is still unclear.

Acknowledgement

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