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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

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REPORT NO. NAWCADPAX/TIM-2015/282

SPECTRUM FATIGUE OF 7075-T651 ALUMINUM ALLOY UNDER OVERLOADING AND UNDERLOADING

by

**E. U. Lee
R. E. Taylor
B. Pregger**

15 March 2016

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DEPARTMENT OF THE NAVY
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
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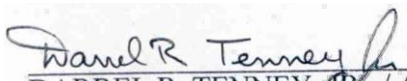
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14. ABSTRACT A study was conducted to clarify the effects of overload, underload, stress ratio, and environment on fatigue crack growth. Fatigue crack growth tests were conducted with a 7075-T651 aluminum alloy under constant amplitude, and over- and under-loading of two different stress ratios, 0.1 and 0.85, in vacuum, air and 1 percent NaCl solution. Under constant amplitude loading, da/dN of R=0.1 and 0.85 was mostly greatest in 1 percent NaCl solution, intermediate in air and lowest in vacuum, and it was greater at R=0.85 than at R=0.1. Furthermore, the da/dN under constant amplitude loading was similar to that of underloading at high ΔK . On the other hand, da/dN was greater under underloading than under overloading, greater in 1 percent NaCl solution, and greater at R=0.85 than at R=0.1. To account for the load spectrum sequence effects, the recently developed cycle-by-cycle fatigue crack growth (FCG) model, UniGrow, was chosen in this study. This model regards the FCG as a process of successive crack re-initiation in the crack tip region, controlled by a two-parameter driving force. Employing the UniGrow equation, the variation of crack length with number of loading cycle was predicted. The prediction and the fatigue test life were found to agree fairly closely.					
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SUMMARY

Fatigue tests of 7075-T651 aluminum alloy were conducted under constant amplitude loading, and spectrum loadings of overload and underload in vacuum of 4×10^{-8} torr, laboratory air of relative humidity about 50 percent and aqueous 1 percent NaCl solution of pH 2 at ambient temperature. The loading frequency was about 5 Hz, the growing crack length was measured, using direct current potential drop technique, and the fatigue crack growth rate was determined. The recently developed cycle-by-cycle fatigue crack growth (FCG) model, UniGrow, was studied to find out whether this model is applicable for the clarification of the load spectrum sequence effect. Employing the UniGrow equation, the variation of crack length with number of loading cycle was predicted. The prediction and the fatigue test life were compared and evaluated.

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INTRODUCTION

Most structural members and machine components are subjected in service to cyclic loadings of varying amplitude. The variation in stress level follows either a regular or random pattern. The resulting crack growth is affected by the applied load sequence in the early stage (crack initiation) and in the later stage (crack propagation) of fatigue. The fatigue crack growth is known to be retarded by tensile overloads and accelerated by compressive overloads (underloads). However, the phenomenon and mechanism of the load sequence effects, especially those of overloading and underloading, on fatigue crack growth in different environments remain to be clarified.

BACKGROUND

Structural components are mostly subjected to variable amplitude or spectrum fatigue loading in various service environments. Blades in gas turbine engines experience low-amplitude, high-frequency vibration during operation, superimposed on a relatively smaller number of cycles of fatigue loading due to start-up and shut-down. Railway tracks are subjected to random loading depending on the frequency and loading conditions associated with the passage of trains. The rotors and bearings of a turbo-generator are subjected to an overload (OL) during every start-up. On the ground, the lower wing skin of the aircraft is under compression. During flight, variable loads due to gust are superimposed on a mean tensile load corresponding to an undisturbed flight. The transition from a compressive load on the ground to a tensile load during flight is an important load cycle in itself and is usually referred to as a ground-air-ground cycle.

The fatigue crack growth under spectrum loading is affected by load interaction, such as crack growth acceleration, retardation or even arrest (1, 2). Due to the load interaction effects, reliability, and life assessment of structural components entails considerable difficulties under spectrum loading. For instance, high OL peaks cause retardation effects whereas underload (UL) peaks accelerate the crack growth and weaken the preceding retardation effect (3-6).

To account for the load spectrum effects, cycle-by-cycle fatigue crack growth prediction models were developed. They are divided into three main groups, Willenborg (3), Wheeler (4), and UniGrow (7, 8) ones. The first and second ones consider that the current cyclic crack tip plastic zone develops inside a larger zone created by the preceding OL. Furthermore, the second one is based on crack closure, and includes plasticity-induced crack closure model (9) and strip yield model (10). Third group, the unified two parameter model is based on the elastic-plastic crack tip stress-strain history (7, 8).

In addition, the fatigue crack growth is also influenced strongly by environments. It is well established that seawater and other aggressive environments accelerate fatigue crack growth (11, 12). However, other investigators (13-18) reported that aggressive environments could cause fatigue crack growth retardation or even arrest.

Creager and Paris (19) showed that crack blunting can decrease the stress intensity factor and hence cause crack growth retardation. Bristoll, and Roeleveld, (14) and Johnson et al (15)

proposed that this could account for fatigue crack growth arrest in structural steel during fatigue at 0.1 Hz under tidal immersion conditions. So did Radon et al for crack stoppage in mild steel at 0.25 Hz in 3.5 percent NaCl solution and Atkinson and Lindley (20) for A533 steel fatigued in distilled water at 90°C. Crack branching will also decrease the stress intensity factor, as shown by Vitek (21). Tu and Seth (17) used this argument to account for the increase in threshold ΔK level for turbine rotor steels when fatigued in steam instead of air. Another mechanism for crack retardation is corrosion product wedging, which increases the minimum K and hence reduce the stress intensity range ΔK . Nordmark and Fricke (18) produced strong evidence that this was the reason for crack arrest of 7475-T351 aluminum alloy fatigued in artificial sump water. They showed that minimum crack-opening displacement, which can be directly related to K, increased when fatigue crack growth arrest occurred. Another result (13) showed crack retardation and stoppage in two structural steels during constant amplitude fatigue at 10 Hz frequency in oxygen-saturated seawater.

PURPOSE

This study is initiated to clarify the fatigue crack growth behavior of a 7075-T651 aluminum alloy under spectrum loading with periodic OL or UL cycles in different environments. Furthermore, the possible mechanisms, synergistic effects and implications are considered.

METHODS

SPECIMEN

Middle-tension M(T) specimen was machined in L-T orientation from a 7075-T651 aluminum alloy extrusion of 127x127x394 mm (5x5x15.5 in.). It was 102 mm (4 in.) wide, 235 mm (9.3 in.) long and 2 mm (0.086 in.) thick, and its center notch was 3 mm (1/8 in.) long. Its mechanical properties were UTS 538 MPa (78 ksi), YS 446 MPa (65 ksi) and elongation 11 percent.

FATIGUE TESTS

The fatigue tests were conducted under constant amplitude loading and spectrum loading with periodic OL or UL cycles at ambient temperature in an MTS machine, Figure A-1. The loading frequency was 5 Hz, the growing crack length $2a$ was measured, employing direct current potential drop technique, and the fatigue crack growth rate da/dN was computed. Subsequently, half crack length vs. number of loading cycle a vs. N and fatigue crack growth rate vs. stress intensity range da/dN vs. ΔK were plotted. The main features of the loadings were:

CONSTANT AMPLITUDE TYPE

Constant Amplitude Loading of Stress Ratio $R=0.1$ or 0.85 in Vacuum of 4×10^{-8} Torr , Air and 1 percent NaCl Solution of pH 2

OVERLOAD TYPE

A 100 percent OL-Spike at Every 10,000 Cycles of $R=0.1$ or 0.8 in Vacuum of 4×10^{-8} Torr and 1 percent NaCl Solution of pH 2, Figure A-2

UNDERLOAD TYPE

A 100 percent UL-Spike at Every 10,000 Cycles of $R=0.1$ or 0.85 in Vacuum of 4×10^{-8} Torr and 1 percent NaCl Solution of pH 2, Figure A-2

FRACTOGRAPHY

After the fatigue test, the morphology of the specimen fracture surface was examined with a JEOL JSM-6460LV scanning electron microscope, operated at an acceleration voltage of 20 kV.

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EXPERIMENTAL RESULTS

CONSTANT AMPLITUDE LOADING FATIGUE

Figure A-3 shows the effect of environment on fatigue crack growth under constant amplitude loading at two different stress ratios 0.1 and 0.85. Each of the two sets of fatigue crack growth rate vs stress intensity range (da/dN vs ΔK) curves for $R=0.1$ and 0.85 consists of three curves for three different test environments, vacuum (dark), air (red) and 1 percent NaCl solution (yellow).

In the case of $R=0.1$, at lower ΔK , the da/dN is greatest in air, intermediate in NaCl solution and lowest in vacuum. The slower fatigue crack growth in NaCl solution than in air is attributable to corrosion product-induced crack closure. At intermediate ΔK , da/dN is similar in air and NaCl solution, and it is lowest in vacuum. At high ΔK , the three curves tend to converge together and the fatigue crack growth rates are similar in the three environments.

In the case of $R=0.85$, at low and intermediate ΔK , the da/dN is slightly greater in NaCl solution, intermediate in air and lowest in vacuum. This evidences that the corrosion product-induced crack closure is absent at $R=0.85$. At high ΔK , the three curves converge together and the fatigue crack growth rates become similar in the three environments.

Figure A-4 shows the effect of R on da/dN and the threshold stress intensity range for fatigue crack growth ΔK_{th} in the three environments. The red curve indicates the result of test at $R=0.85$ and the dark one that at $R=0.1$. The da/dN is greater and the ΔK_{th} is smaller at $R=0.85$ than at $R=0.1$ in all of the three environments.

OVERLOADING AND UNDERLOADING FATIGUE

FATIGUE CRACK LENGTH

Figure A-5 shows the variation of half crack length with number of loading cycle N during OL and UL spectrum loading at $R=0.1$ in vacuum and 1 percent NaCl solution. The crack growth is faster and the fatigue life is shorter under the UL spectrum loading than the OL one in both of the environments, Figures A-5(a) and (b).

Figure A-6 shows the effect of environment on the variation of half crack length with number of loading cycle under OL and UL spectrum loading at $R=0.1$. The crack growth is faster in 1 percent NaCl solution than in vacuum under OL spectrum loading, Figure A-6(a), whereas they are similar in the two environments under UL spectrum loading, Figure A-6(b).

Figure A-7 shows the effect of spectrum loading on the variation of half crack length with number of loading cycle at $R=0.85$ in vacuum and 1 percent NaCl solution. The crack growth under UL spectrum loading is slightly faster and the fatigue life is slightly shorter than under OL one, Figure A-7(a). On the other hand, the crack growth is much faster and the fatigue life is

much shorter under UL spectrum loading than under OL one in 1 percent NaCl solution, Figure A-7(b).

Figure A-8 shows the effect of environment on the variation of half crack length with number of loading cycle at $R=0.85$ in vacuum and 1 percent NaCl solution. The crack growth is faster and the fatigue life is shorter in 1 percent NaCl solution than in vacuum under both of the OL and UL spectrum loadings, Figure A-8(a) and (b).

FATIGUE CRACK GROWTH RATE

Figure A-9 shows the effect of loading on fatigue crack growth rate da/dN at $R=0.1$ in vacuum and 1 percent NaCl solution. Yellow curve indicates constant amplitude loading, red one overloading, and dark one underloading. From these two sets of curve, it is clear that:

- In vacuum, the da/dN is greater for underloading than for constant amplitude loading at lower ΔK , but it is similar at higher ΔK . That is, the fatigue crack growth is accelerated by underloading at lower ΔK in vacuum.
- In 1 percent NaCl solution, the da/dN is similar for constant amplitude loading and underloading within the range of ΔK employed.
- Compared to the da/dN under constant amplitude loading and underloading, the da/dN under overloading is lower in vacuum and 1 percent NaCl solution. This observation indicates that the fatigue crack growth is retarded by overloading in both environments.

Figure A-10 shows the effect of environment on fatigue crack growth rate under overloading and underloading at $R=0.1$. Red curve indicates the test data in 1 percent NaCl solution and dark one that in vacuum. From these plots, it is clear that the fatigue crack growth is faster in 1 percent NaCl solution than in vacuum under overloading and underloading, Figures 10(a) and (b).

Figure A-11 shows the effect of loading on fatigue crack growth rate at $R=0.85$ in 1 percent NaCl solution. Yellow curve indicates the constant amplitude loading data, red one the overloading data and dark one the underloading data. From these plots, it is clear that:

- The da/dN is mostly similar for constant amplitude loading and underloading and
- The da/dN is lowest for overloading, indicating retardation of fatigue crack growth by overloading.

Figure A-12 shows the effect of environment on fatigue crack growth rate under overloading at $R=0.85$. Red curve indicates the result of test in 1 percent NaCl solution, and dark one that in vacuum. From this plot, it is clear that the da/dN is greater in 1 percent NaCl solution than in vacuum for overloading.

FRACTOGRAPH

Typical fractographs of those specimens, subjected to OL and UL spectrum fatigue loading at $R=0.1$ in vacuum, are shown in Figures A-13 and -14. The optical fractograph of the OL spectrum fatigue tested specimen shows beach-marks, Figure 13(a), whereas that of UL spectrum fatigue tested shows quite faint ones, Figure A-13(b). The SEM fractograph of the OL spectrum fatigue tested specimen shows fatigue striations clearly, Figure A-14(a), whereas that of UL spectrum fatigue tested specimen faint ones, Figure A-14(b).

The spacing of the fatigue striation is measured to be increasing with increasing crack length, initially steeply and then moderately, as shown in Figure A-15.

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DISCUSSION

CRACK GROWTH RETARDATION AND ACCELERATION

As observed in this study, other investigators also observed crack growth retardation and acceleration during variable amplitude fatigue loading. For example, on application of a single peak OL, the crack first accelerates [22, 23], and this is followed by a prolonged period of decelerated crack growth. On the other hand, after a single compressive UL, a brief acceleration of the crack growth is observable. However, the subsequent crack growth is comparable to that of a single peak tensile OL.

Several mechanisms have been proposed to account for the crack growth retardation following a single OL. Some of them include: (i) crack tip blunting [19]; (ii) deflection or bifurcation of the crack [24]; (iii) residual compressive stresses ahead of the crack tip [3, 4], and (iv) plasticity-induced crack closure in the wake of the crack tip [25, 26]. However, in this study, any crack deflection or bifurcation has not been detected during overloading. After a single compressive underloading, tensile residual stress is generated behind the crack tip. The tensile stress results in higher crack tip driving force for crack growth and an instantaneous acceleration of crack growth [27].

UNIGROW MODEL

The UniGrow model is based on the elastic-plastic crack tip stress-strain history. This model regards the FCG as a process of successive crack re-initiation in the crack tip region, controlled by a two-parameter (K_{max} and ΔK) driving force. The basic equation of this model is $da/dN = C[(K_{max,tot})^p(\Delta K_{tot})^{(1-p)}]^\gamma = C[\Delta K]^\gamma$, $a = \int C[\Delta K]^\gamma dN$

where

$$C = 2\rho^*[(\psi_{y,1})^2/2^{(n'+3)/(n'+1)}\sigma'_f\epsilon'_f\pi E\rho^*]^{-\{1/(b+c)\}}, \quad p = n'/(n' + 1), \quad \gamma = -2/(b + c)$$

a: half crack length, b: fatigue strength exponent, c: fatigue ductility exponent, C: fatigue crack growth constant, $K_{max,tot}$ =total maximum stress intensity factor, n' : cyclic strain hardening exponent, p: driving force constant, ϵ'_f : fatigue ductility coefficient, γ : fatigue crack growth equation exponent, ρ^* : notch tip radius or elementary material block size, σ'_f : fatigue strength coefficient, ψ_i : average constant corresponding to i th elementary block.

COMPARISON OF TEST RESULT AND UNIGROW PREDICTION

Figures A-16 and A-17 compare the test result, Figure A-5, and the corresponding UniGrow prediction for the variation of crack length vs number of loading cycle under OL and UL spectrum loading in vacuum and 1 percent NaCl solution, respectively.

In vacuum, the prediction life is quite shorter than the test life under OL spectrum loading, whereas the test data and prediction are close under UL spectrum loading, Figure A-16. This

comparison indicates that the UniGrow model accounts for the FCG retardation by tensile OL too little in vacuum.

In 1 percent NaCl solution, the prediction life is shorter than the test life under OL spectrum loading, whereas the test data and prediction are in good agreement under UL spectrum loading, Figure A-17.

CONCLUSIONS

Under constant amplitude loading, overloading and underloading, fatigue crack growth rate is greater at stress ratio 0.85 than at 0.1.

1 percent NaCl solution accelerates but vacuum retards the fatigue crack growth.

OL retards but the UL accelerates the fatigue crack growth in vacuum and 1 percent NaCl solution.

The UniGrow model provides close estimate of fatigue crack growth (FCG) for underloading, but conservative one for overloading in vacuum and 1 percent NaCl solution. This evidences that the UniGrow model accounts for the FCG acceleration by underloading correctly, but it does not for the FCG retardation by overloading.

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Figure A-1: Test Set-Up in MTS Machine

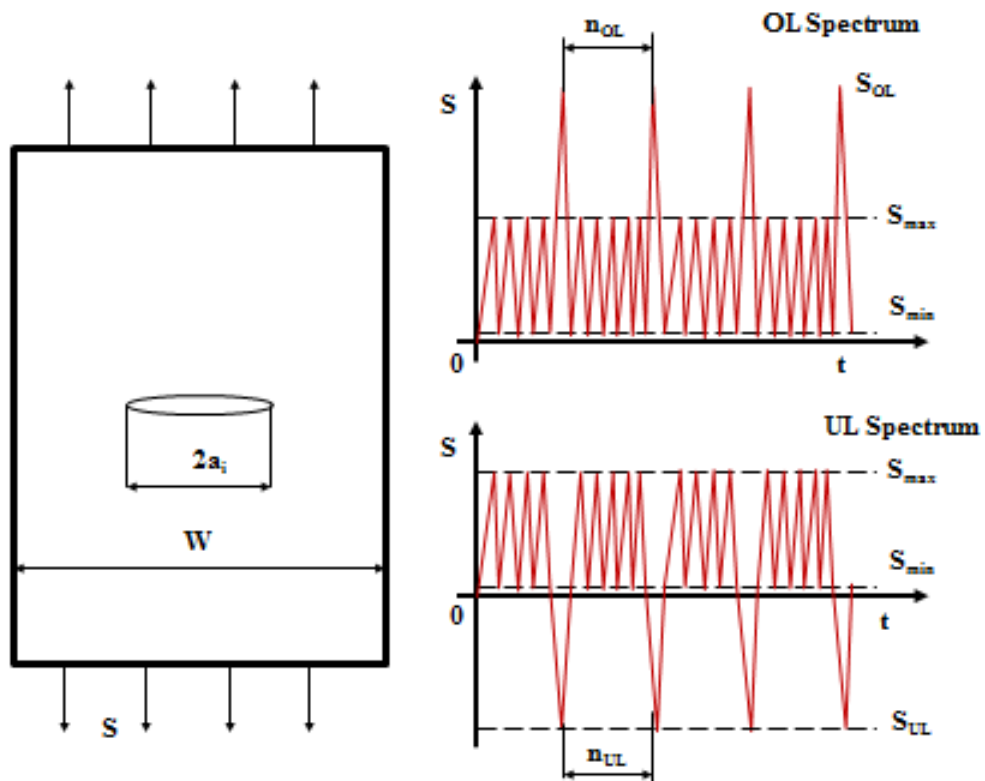


Figure A-2: Overload and Underload Spectrums

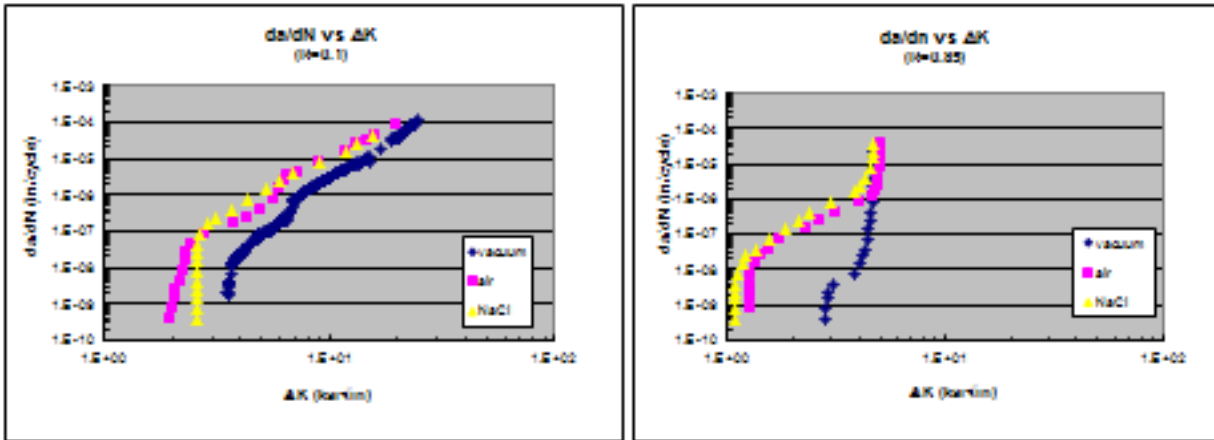


Figure A-3: Effect of Environment on da/dN under Constant Amplitude Loading at $R=0.1$ and 0.85

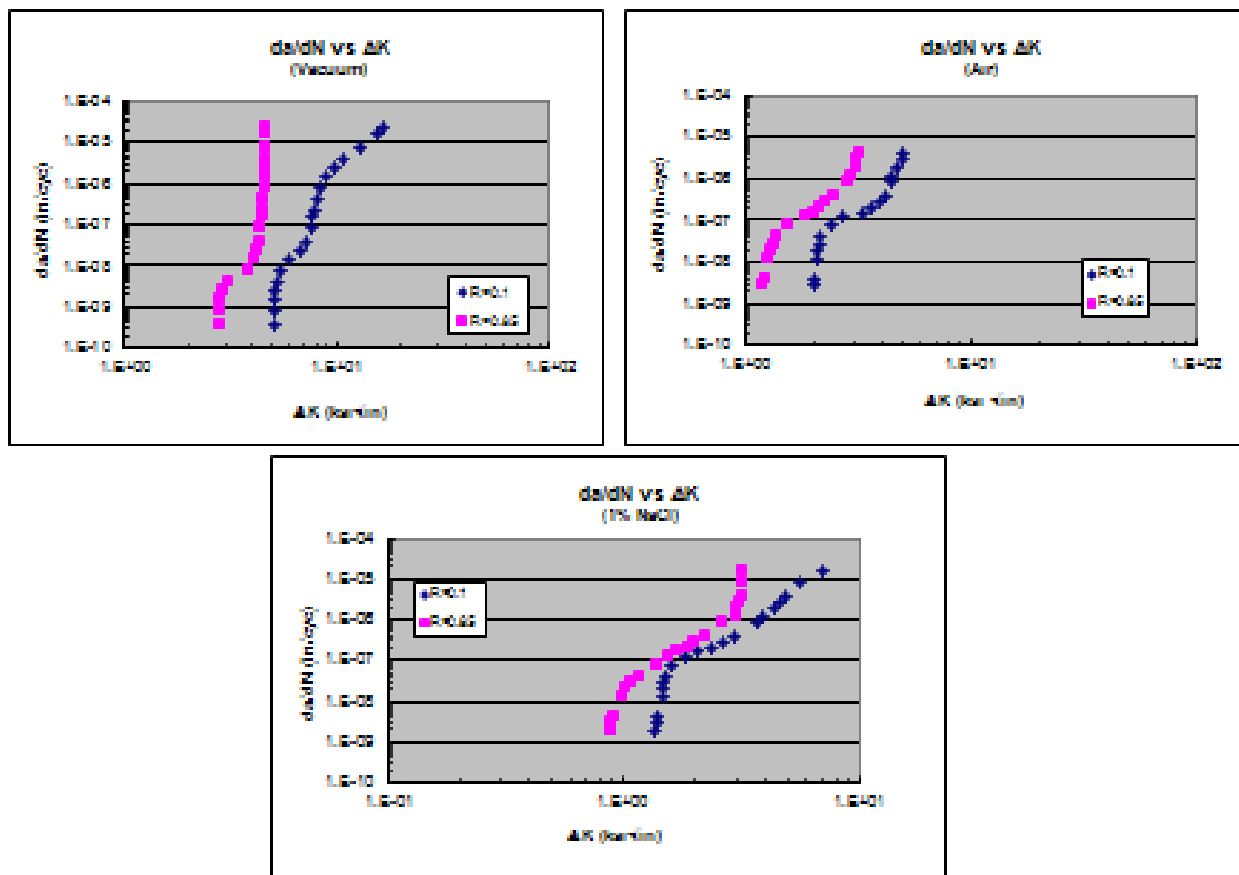


Figure A-4: Effect of R on da/dN under Constant Amplitude Loading in Vacuum, Air, and 1 Percent NaCl Solution

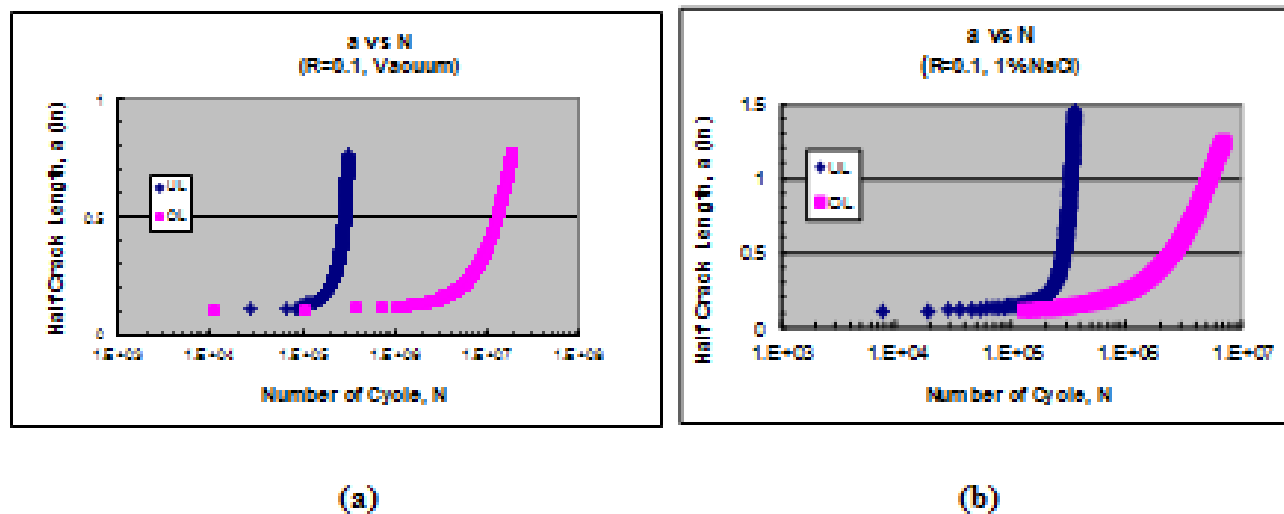


Figure A-5: Variation of Half Crack Length with Number of Loading Cycle at $R=0.1$ in a Vacuum and 1 Percent NaCl Solution under Overloading and Underloading

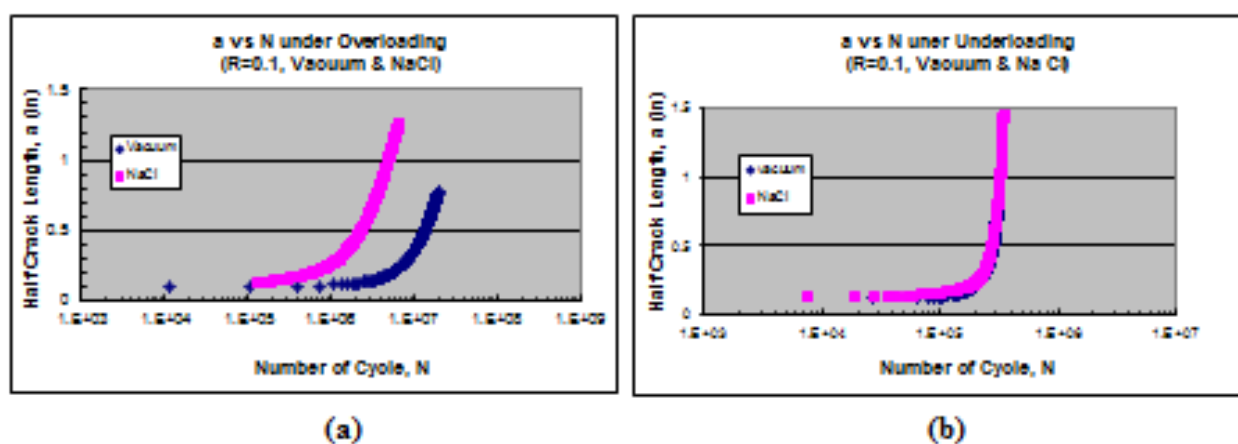


Figure A-6: Variation of Half Crack Length with Number of Loading Cycle at $R=0.1$ under Overloading and Underloading in Vacuum and 1 Percent NaCl Solution

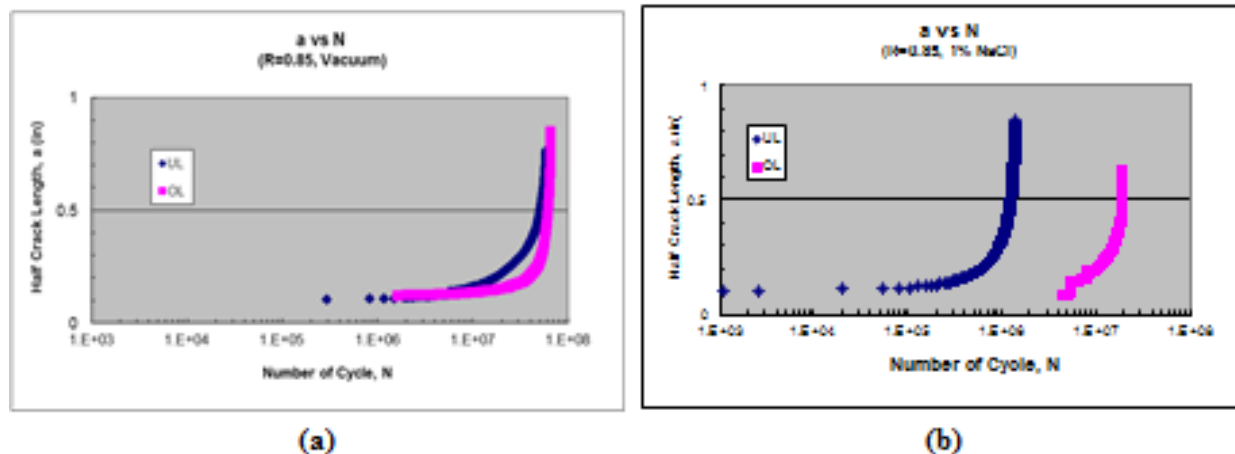


Figure A-7: Variation of Half Crack Length with Number of Loading Cycle at $R=0.85$ in Vacuum and 1 Percent NaCl Solution under Overloading and Underloading

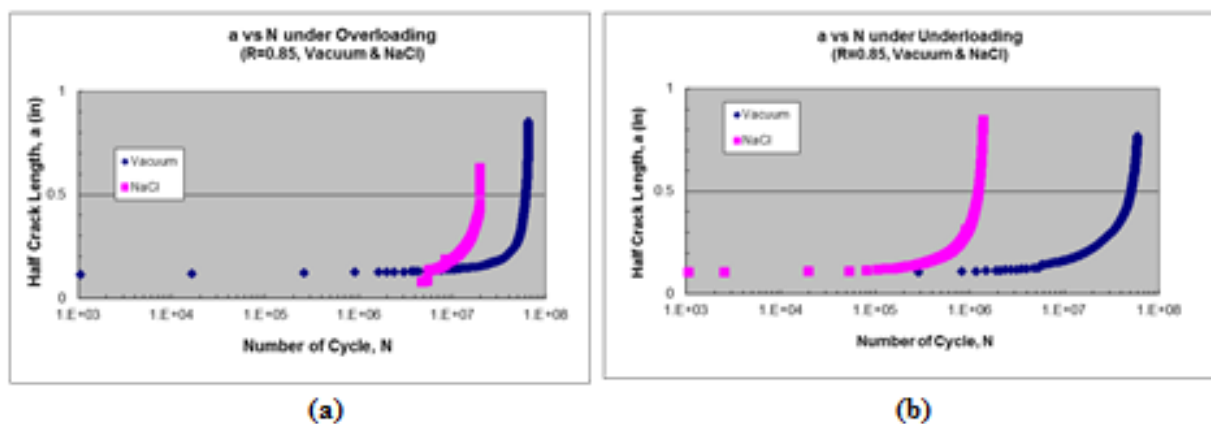


Figure A-8: Variation of Half Crack Length with Number of Loading Cycle under Overloading and Underloading in Vacuum and 1 Percent NaCl Solution

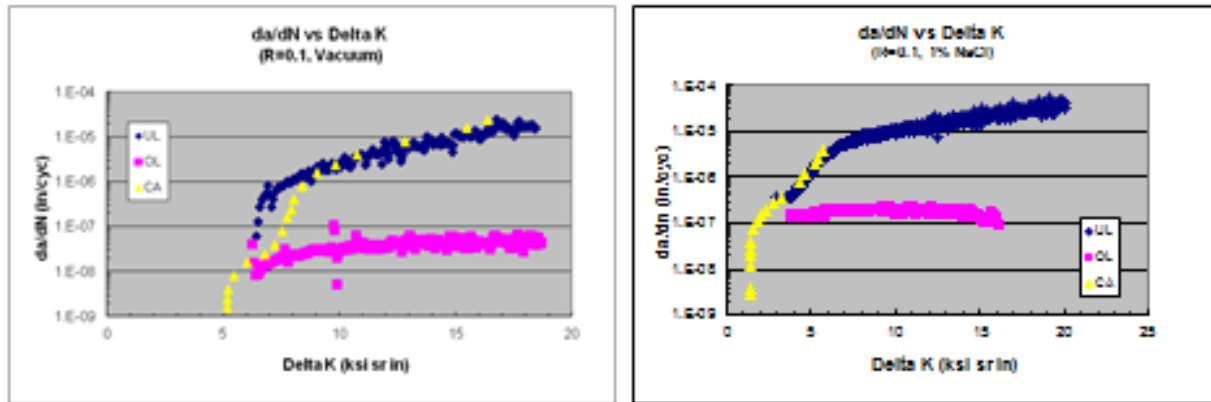


Figure A-9: Effect of Loading on Fatigue Crack Growth Rate at R=0.1 in Vacuum and 1 Percent NaCl Solution

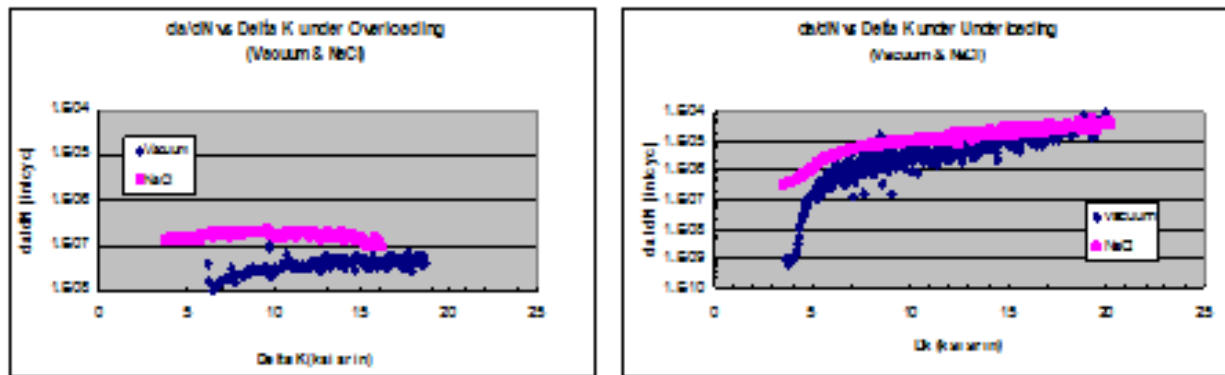


Figure A-10: Effect of Environment on Fatigue Crack Growth Rate at R=0.1 Under Overloading and Underloading

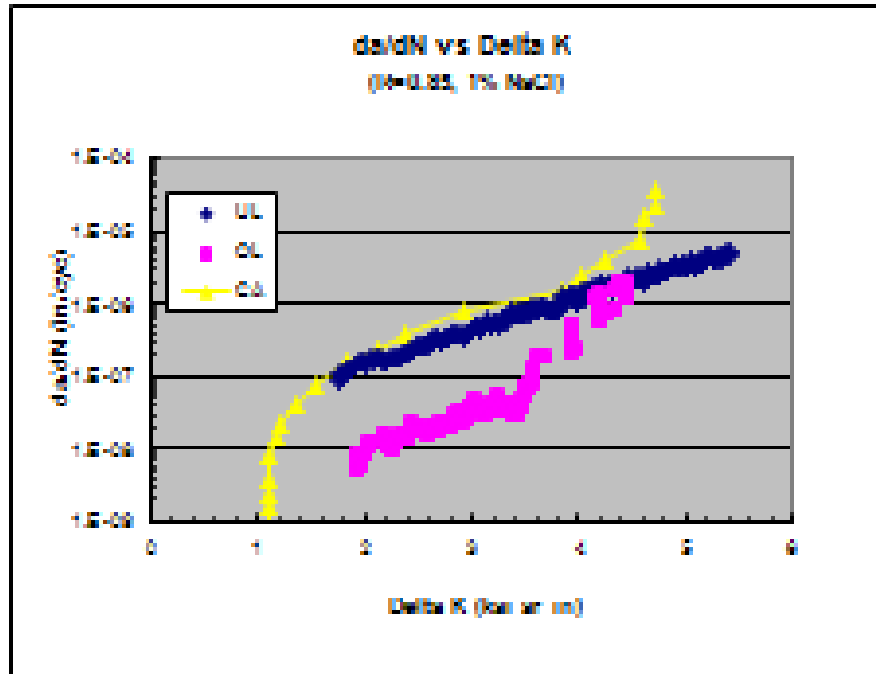


Figure A-11: Effect of Loading on Fatigue Crack Growth Rate at R=0.85 in 1 Percent NaCl Solution

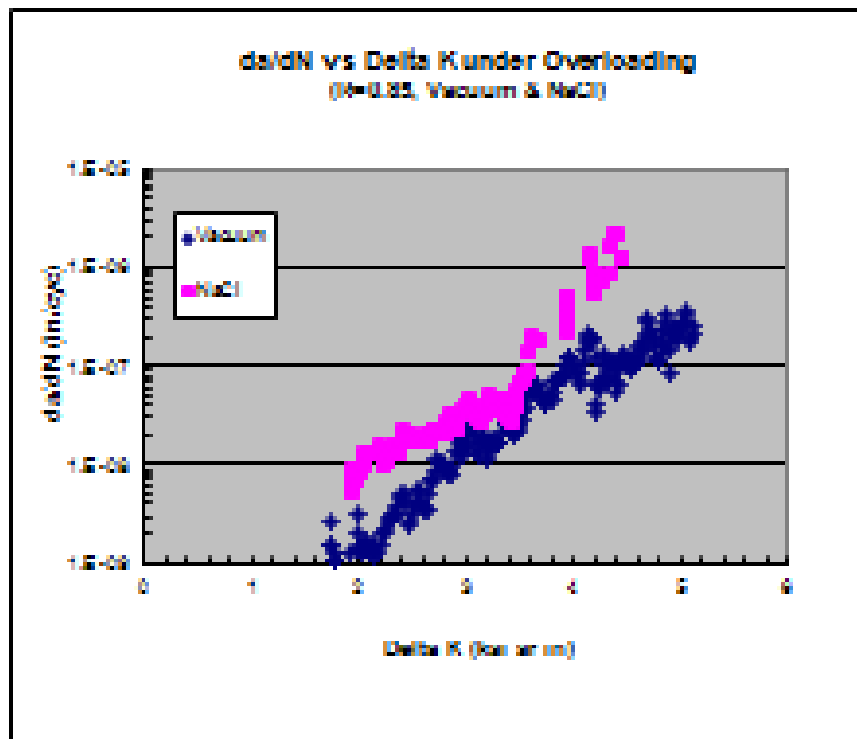


Figure A-12: Effect of Environment on Fatigue Crack Growth Rate at R=0.85 under Overloading

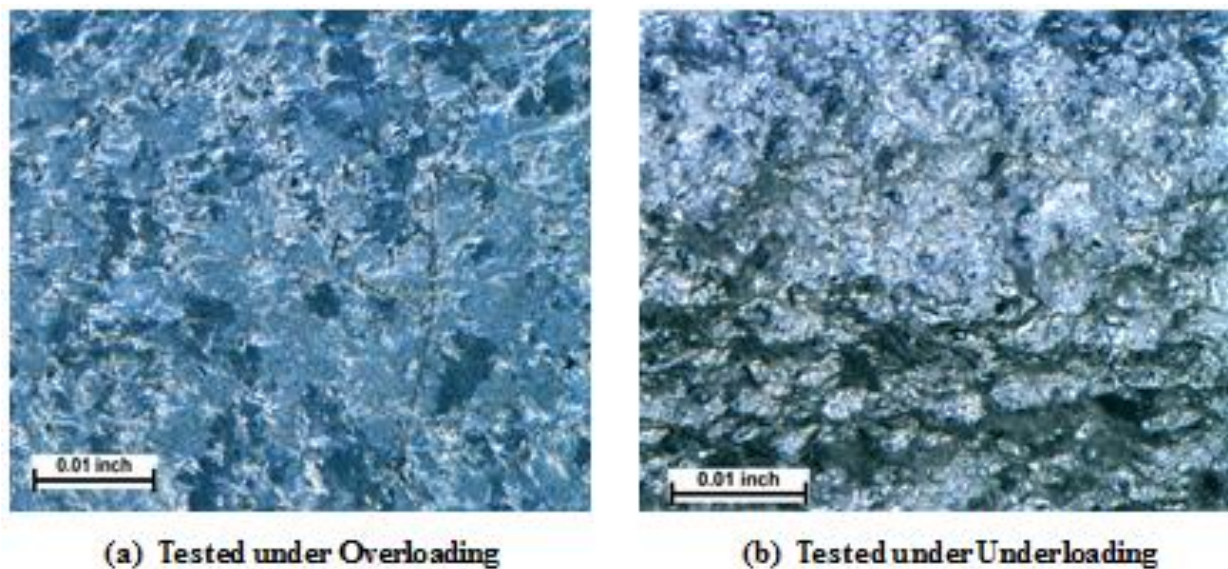


Figure A-13: Optical Fractographs

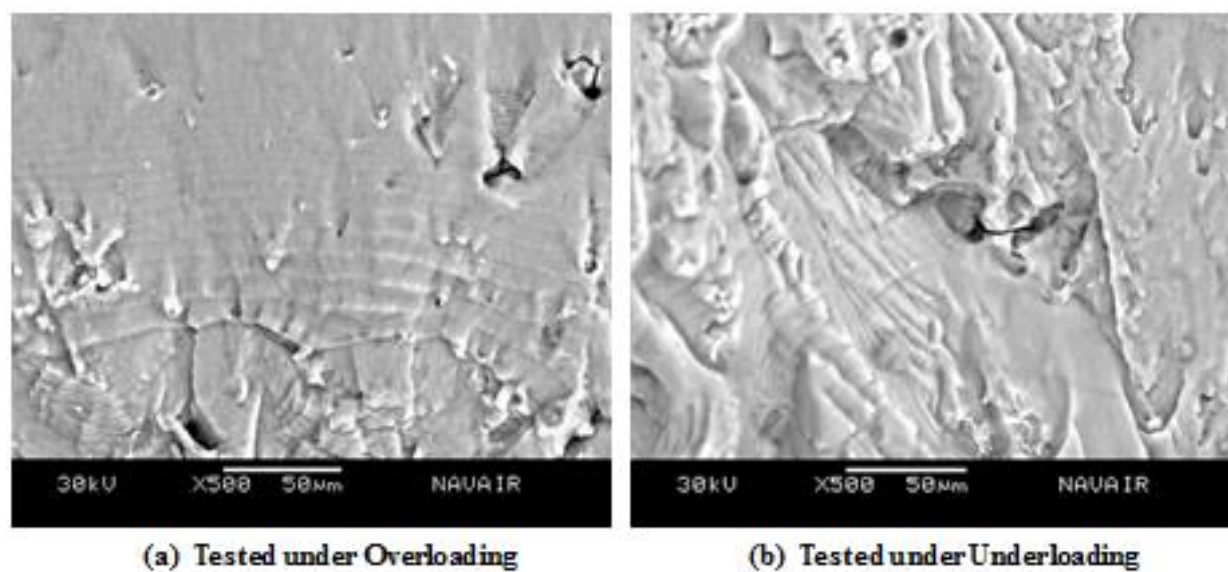


Figure A-14: SEM Fractographs

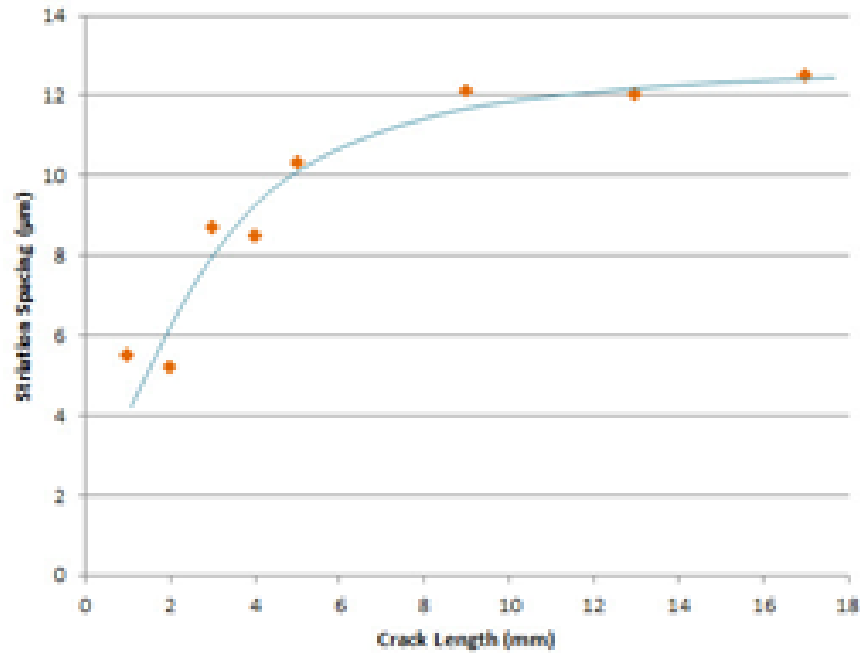


Figure A-15: Variation of Striation Spacing with Crack Length

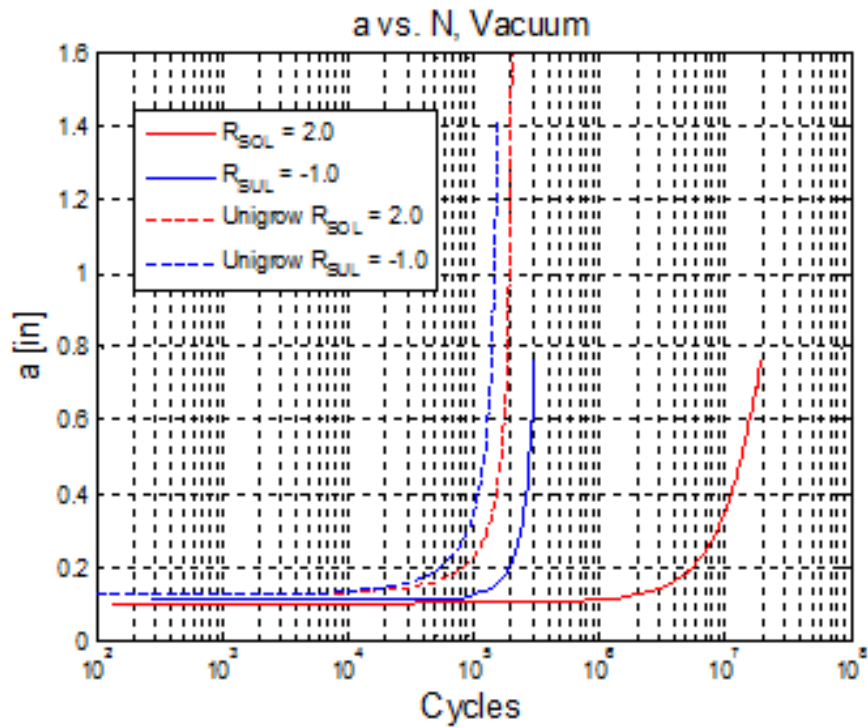
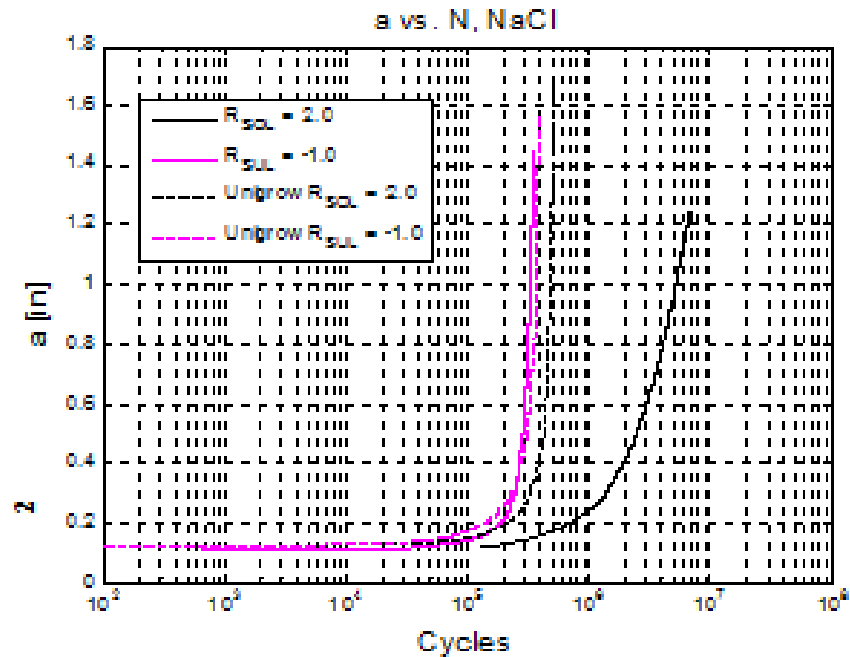


Figure A-16: Graphic Comparison of Test Data and UniGrow Model Prediction for Overload and Underload Spectrums in Vacuum



$R_{SOL} = 2.0$: Overload Ratio = A 100% OL at Every 10,000 Cycles = Peak OL/Max. Load
 $R_{SUL} = -1.0$: Underload Ratio = A 100% UL at Every 10,000 Cycles = Peak UL/Max. Load

Figure A-17: Graphic Comparison of Test Data and UniGrow Model Prediction for Overload and Underload Spectrums in 1 Percent NaCl Solution

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