INITIAL RESULTS FROM DSTO'S CORROSION STRUCTURAL INTEGRITY ROADMAP

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Abstract

Over the last 15 years, DSTO has developed several successful models of how corrosion affects aircraft structural integrity. DSTO is now working to transfer these models into service on Royal Australian Air Force aircraft. This paper outlines the models developed, the program being followed to transfer these models to service and presents some of the initial results of the program.

1 Introduction

Like many other aircraft operators, the Royal Australian Air Force (RAAF) faces a major challenge in managing corrosion damage in its fleet. This paper presents initial results and models from DSTO's corrosion structural integrity roadmap [1]. It also gives an overview of how these models will be applied to RAAF aircraft to predict the effects of corrosion on structural integrity.

A survey of US aircraft incidents by Hoeppner *et al.* [2] showed that corrosion is fundamentally a safety issue. Corrosion maintenance is expensive and time consuming but it is only needed because corrosion affects safety-of-flight; otherwise there would be no need to repair corrosion damage.

The incidence of corrosion and the cost of corrosion maintenance both increase as aircraft age. This is because corrosion protection systems break down over time and the only currently accepted way of managing corrosion damage is its immediate removal. This policy removes aircraft from service while corrosion repairs are undertaken. In addition to the direct cost of maintenance, the lack of aircraft availability also has economic and operational costs.

As a result, a policy that would allow corrosion repairs to be delayed until a major service could significantly reduce the cost of aircraft ownership and increase availability without compromising safety.

Such a policy, however, requires accurate models of the effects of corrosion damage on structural integrity. DSTO has conducted a large volume of work and has had several such models. Figure 1 shows the history of DSTO's research in this area since 1996.

The Cole *et al.* report [3] which DSTO published in 1997 surveyed the then state-of-the-art. It identified pitting and exfoliation corrosion as critical forms of corrosion with respect to structural integrity. Since then, DSTO has conducted extensive experimental programs on these forms of corrosion, modeled their effects and has found that it could predict the fatigue lives of corroded materials with good accuracy. Figure 2 shows the method proposed for transferring these models into service on RAAF aircraft. This method uses a staged approach to increase the likelihood that the models developed will be accepted into service.

Based on its past research and the needs of the RAAF, DSTO proposes to concentrate its future research into corrosion structural integrity on the following:

1. Developing a certification plan for pitting corrosion (Section 2.1),
2. Developing a certification plan for exfoliation (Section 2.2),
3. Developing a predictive model for the structural integrity effects of intergranular corrosion (Section 3.2), and
4. Integrating the above models into the RAAF's Environmental Degradation Management toolbox (Section 4).

These research areas have been selected because of their significance to aircraft structural integrity and because DSTO has either previous research experience or links with other research agencies with experience in these areas.

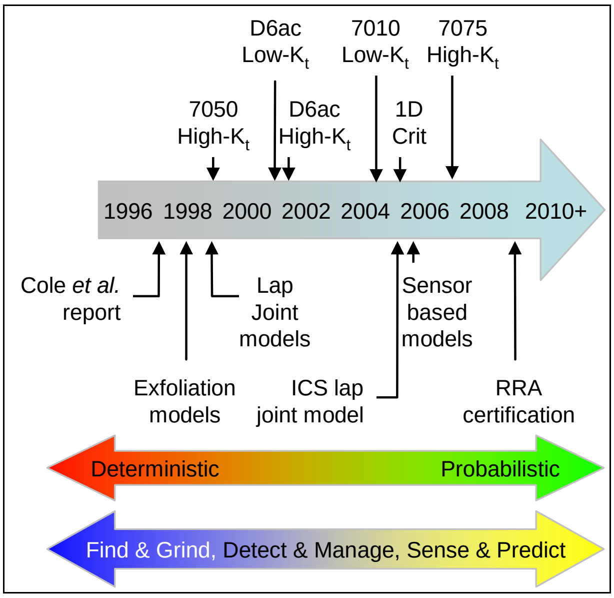

Figure 1: Timeline of DSTO research into the effects of corrosion on aircraft structural integrity

2 Past Work

As stated, DSTO has been working on models of the effect of corrosion on structural integrity since 1997. This section provides an overview of this work including a summary of its major findings. For brevity, the discussion in this section is restricted to pitting and exfoliation corrosion. Other modes of corrosion are discussed in [1].

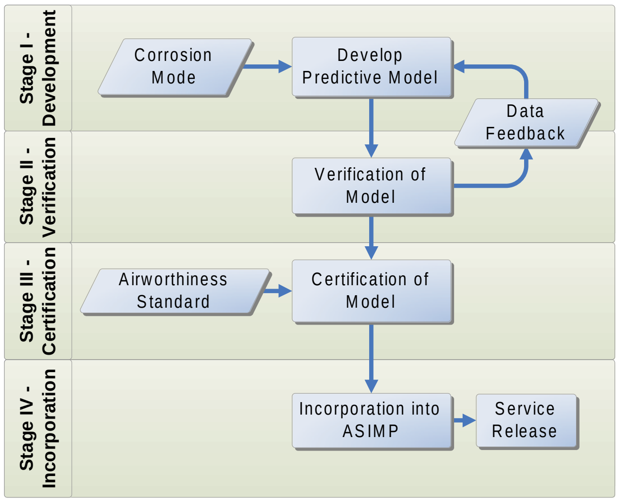

Figure 2: Flowchart for the transfer of DSTO's corrosion structural integrity models into RAAF service

2.1 Pitting Corrosion

DSTO has investigated the effect of corrosion on the fatigue endurance of three aluminum alloys (7010-T7651, 7050-T7451 and 7075-T6) [4-7] and one steel (D6ac) [8]. This research was based on decoupling active corrosion from fatigue and as such used pre-corroded fatigue specimens [8]. Figure 3 shows that the mean pit width and depth obtained in each alloy were quite different [1]. This was due the different microstructures and surface treatments of each alloy and the differences in the corrosion protocols used.

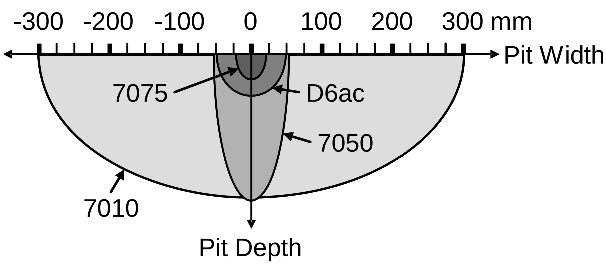

Figure 3: Comparison of mean pit width and depth from each of DSTO's pitting corrosion research projects

2.1.1 7050-T7451

In 1998 DSTO and the USAF started a joint one-year research project on how prior pitting corrosion affects the structural integrity of aluminum alloys. The USAF worked on 2024-T3 [9] while DSTO worked on 7050-T7451 [7].

DSTO's interest in 7050-T7451 came from the in-flight loss of a trailing edge flap from a RAAF F/A-18 [10] in the 1990s. This alloy is the primary structural alloy for the F/A-18 and the lug that held the trailing edge flap to the aircraft was made of this material [7]. DSTO's project used specimens with a central hole to simulate the lug's high stress concentration factor (k_t).

This project found that pitting corrosion greatly reduced the fatigue endurance of pitted high-k_t specimens. A scanning electron microscope was used to measure the dimensions of the corrosion pits on the fracture surfaces of the specimens. The fatigue crack growth prediction software AFGROW was then used to model the fatigue life of the specimens using these dimensions. It was found that pit tip radius had the strongest effect on fatigue life. However, this metric cannot be measured in-service. Therefore, pit depth was used as the primary metric, which was referred to as an equivalent crack size (ECS). Conversely, the width of the pit in these high-k_t specimens was found to be insignificant. This conclusion was supported by comparing finite element models of narrow and wide pits with a model for a crack, see Figure 4.

2.1.2 D6ac

DSTO next studied how prior pitting corrosion affected the fatigue life of the steel D6ac [8] which was used in the wing pivot fittings and the wing carry through box of the now retired F-111. This pitting consisted of smooth hemispherical pits in service and these were replicated in the laboratory using constant current electro-chemistry. The regular shape of the corrosion pits combined with an accurate in-service non-destructive inspection technique, magnetic rubber, meant that the model developed was very accurate.

Given the corrosion pit morphology and the detailed understanding of the stress field, DSTO was able to use its ECS models to accurately predict in test coupons the location of failure. Unfortunately, the F-111 was retired before the model could be implemented into the fleet. However, this project did show that the effects of prior pitting corrosion could be successfully integrated into lifeing methods.

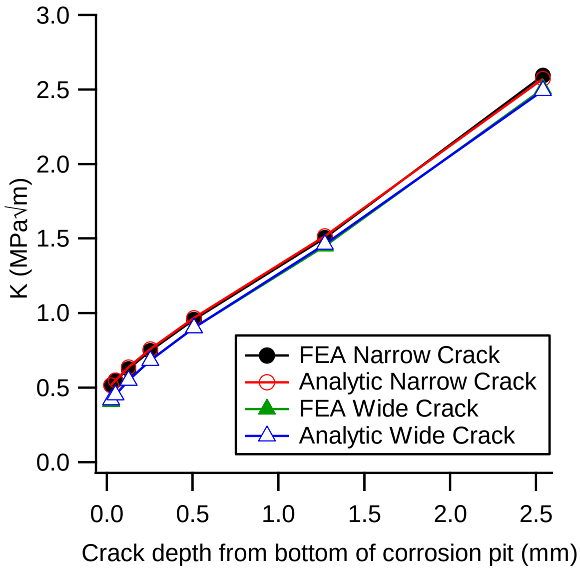

Figure 4: Stress intensity factors (K) calculated using StressCheck, which show only a minimal difference in K of narrow and wide pits with the same pit tip radius [7]

2.1.3 7010-T7651

The 7050-T7451 project was conducted using 32 fatigue specimens. This limited number of specimens combined with their high-k_t geometry meant that the conclusions from that work were specific to the high-k_t condition under which the tests were conducted.

To overcome this, DSTO collaborated with BAE SYSTEMS and CSIRO to design and execute a much larger research project using low-k_t specimens [4, 5]. Over 520 specimens were tested as part of this project. About 420 of these were fatigue life specimens while the remaining 100 were for supplementary tests such as fatigue crack growth, fracture toughness and tensile testing. These specimens were machined from a plate of 7010-T7651, and most were chromic acid anodized prior to corrosion treatment. 7010-T7651 is the primary structural alloy for the BAE SYSTEMS Hawk, which entered service with the RAAF in 2000.

The fatigue life results for the corroded specimens are shown in Figure 5. A set of 25 tests were conducted at each of 12 loading conditions. These results are typical in that fatigue life decreases with increasing stress and decreasing load ratio (R). Also, the scatter in the fatigue lives increased as the applied stress decreased. The shaded region in Figure 5 shows this for R = -0.3

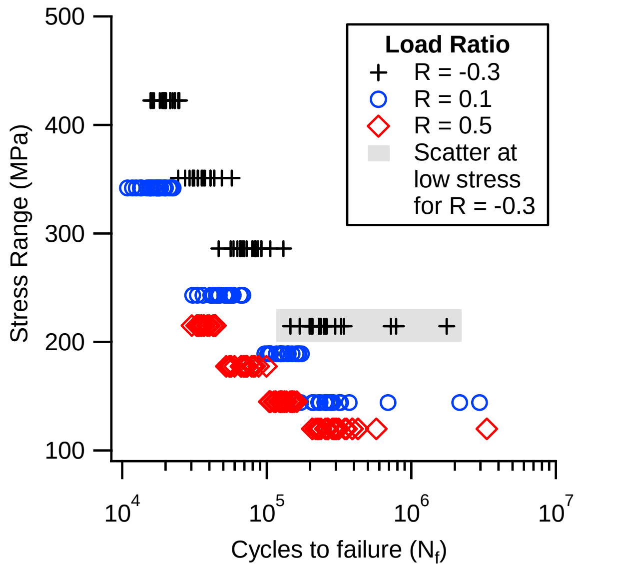

Figure 5: The effect of stress and load ratio on the fatigue life of corroded 7010-T7651

Figure 6 compares the fatigue life results obtained for corroded and uncorroded specimens tested at R = 0.1. The difference in fatigue lives is minimal at high stresses but increases at lower stresses. For example, at a maximum stress of 200 MPa the difference in fatigue life approaches two orders of magnitude.

As with the 7050-T7451 project, the fatigue life of the corroded specimens was modeled using an ECS model based on AFGROW [11]. This required the identification of a suitable metric for pit size. The pit width, depth and area were measured post-failure using a scanning electron microscope. A multiple step linear regression with step-wise variable elimination was then used to identify the pit metric that had the strongest effect on fatigue life. In this case it was found that pit area was the best pit metric. In contrast, pit depth and pit width correlated poorly with fatigue life. These results differ from those obtained from the 7050-T7451 project, which found that pit depth was the best metric. This difference may be due to the 7050-T7451 project investigating end grain corrosion while the 7010-T7651 project looked at surface grain corrosion. The much larger size of the corrosion pits in the 7010-T7651 project, Figure 3, and the difference in specimen geometry (i.e. low-k_t vs. high-k_t) may also be significant.

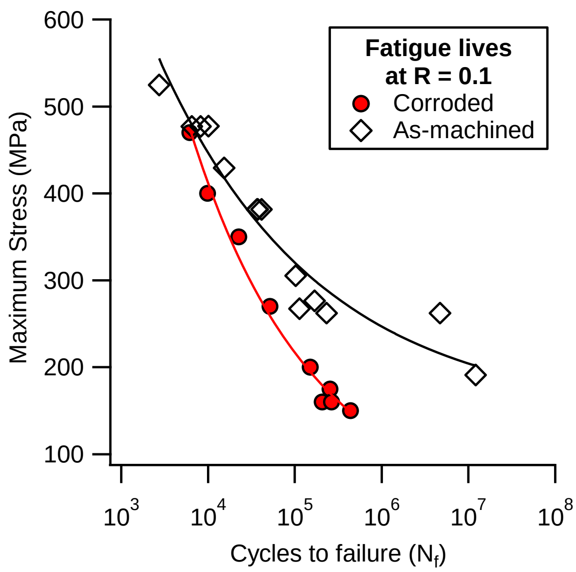

Figure 6: Comparison of the fatigue lives of corroded and uncorroded 7010-T7651 specimens tested at a load ratio of 0.1

The model was then developed using pit area as the pit metric. Two variants of the model were developed using two different fatigue crack growth datasets. The first dataset, which was called the MB-dataset, was developed from measurements of marker band spacing on the fracture surfaces of fatigue life specimens. These were tested using a marker band spectrum developed by NASA [12]. The second dataset, called the CCT-dataset, came from centre crack tension (CCT) specimens.

The model was iterative. It would first predict a fatigue life based on the pit area. The predicted fatigue life was then compared with the experimental fatigue life. After this, the initial crack size was altered so that the predicted life converged on the experimental life to within a given tolerance. The factor used to modify the initial crack size was named the 'crack metric ratio' or CMR. Figure 7 shows the physical meaning of various CMR values.

A separate CMR value was obtained for each of the 300 fatigue tests conducted. When plotted as a histogram these values were found to follow a log-normal distribution which differed for each fatigue crack growth dataset. The mean value of the distribution for the MB-dataset was 1.16, while for the CCT-dataset the mean value was 0.0912. Note that the CMR is a ratio of areas. The ratio of crack lengths is therefore the square root of the CMR. Therefore, the input crack lengths for the MB-dataset were only 8% larger than the crack lengths derived from the pit area metric while the input crack length for the CCT-dataset were 70% smaller than this value. Therefore, the MB-dataset was a much better match to the fatigue behavior of the alloy than the CCT-dataset.

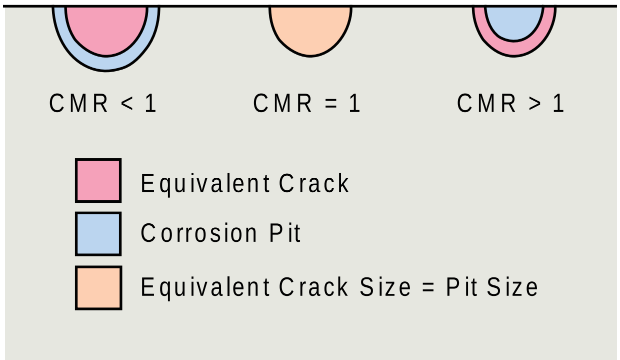

Figure 7: Schematic of the relationship between corrosion pit area, equivalent crack area and crack metric ratio (CMR).

The log-normal distribution of the CMR values meant that it was possible to define a statistically valid standard deviation for the distribution in addition to a mean. Using this standard deviation and the mean it was possible to increase the input initial crack size to ensure that any given proportion of predicted fatigue lives would be conservative, see Figure 8. In the case of the MB-dataset, a CMR of 4.12 would mean that approximately 1 in 1000 fatigue life estimates would be non-conservative.

The above model is considered by DSTO to be a good candidate for in-service use by the RAAF. As such it is DSTO's intention to validate this model and transition it into service on the RAAF's F/A-18. DSTO is currently discussing a trial of the model with the RAAF.

2.1.4 7075-T6

After the completion of the 7010-T7651 project the opportunity arose to test the model developed in that project on the 7075-T6 alloy used in the RAAF AP-3C Orion aircraft [6]. The purpose of this research project was to evaluate if pitting corrosion invalidated the fatigue life assessment method developed in the P-3 Service Life Assessment Program (P3-SLAP) [13]. This research project, therefore, differed from those previously conducted as all fatigue testing was conducted using a variable amplitude (VA) load spectrum. In addition, FASTRAN [14] rather than AFGROW was used to model fatigue crack growth and results were examined against the fatigue life assessment principles of the P3-SLAP. Figure 9 shows the fatigue life results obtained for corroded and uncorroded 7075-T6 in this project. Again, corrosion damage has reduced the fatigue life of the alloy.

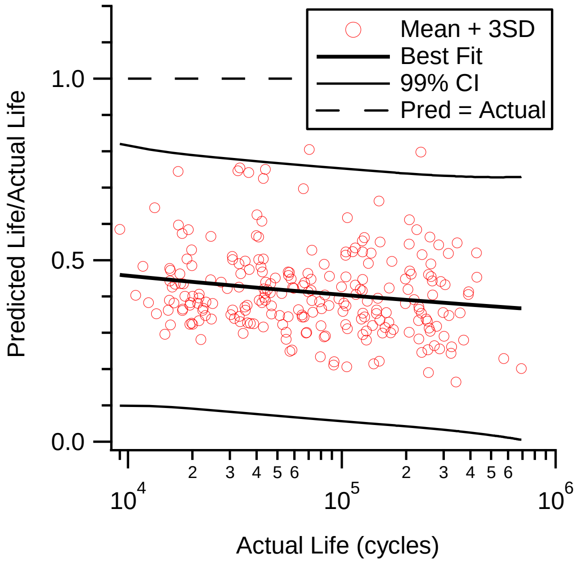

Figure 8: Predicted fatigue lives (normalized against actual life), predicted using mean plus three standard deviations value of log(CMR) ('Mean + 3SD').

2.2 Exfoliation

In addition to its research into pitting corrosion, DSTO has developed two predictive models for the effect of exfoliation corrosion on the fatigue life of the aluminum alloy 2024-T3. One was developed solely by DSTO while the other was developed in collaboration with the National Research Council (NRC) of Canada. These models are described in the two sections that follow.

2.2.1 DSTO Process Zone Model

The first model developed by DSTO was the so-called 'process zone' model [15]. This model assumes that exfoliation can be modeled as a small crack at the base of a notch. It was based on observations of exfoliation corrosion, made using a scanning electron microscope, which suggested the presence of small intergranular cracks at the bottom of exfoliated regions in aluminum alloys. This model is illustrated schematically in Figure 10.

The model was implemented using FASTRAN and calibrated using experimental results. Figure 11 compares the predictions of two variants of the model with some experimental results. The model's predictions capture both the rapid initial drop in the experimental fatigue lives followed by the subsequent slower decline. These two behaviors correspond to the initiation and growth of the corrosion pit, followed by the subsequent reduction of cross-sectional area as the exfoliation corrosion deepens.

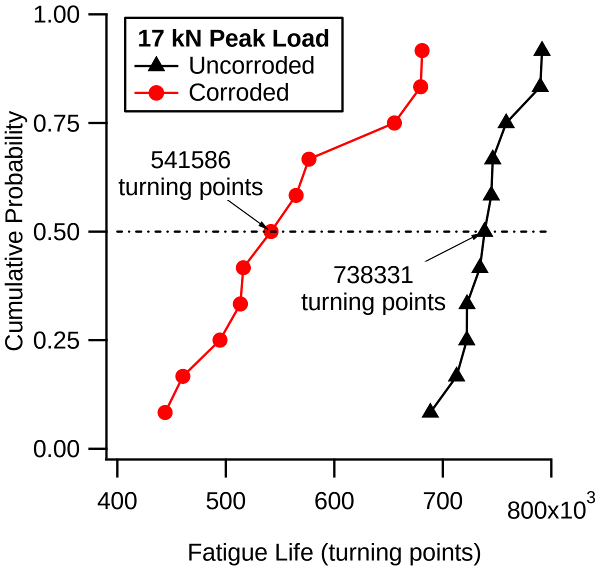

Figure 9: Effect of pitting corrosion on the fatigue life of corroded 7075-T6 at a 17 kN peak load level.

2.2.2 DSTO/NRC ECS Model

Despite its success, the Process Zone model required knowledge of the size of the intergranular crack, which can only be measured using a scanning electron microscope. Given that this cannot be done on in-service aircraft it was decided to develop an ECS model. This was done in collaboration with the NRC of Canada. The model used a Canadian load spectra for the C-130 Hercules. Figure 12 shows some of its results [16].

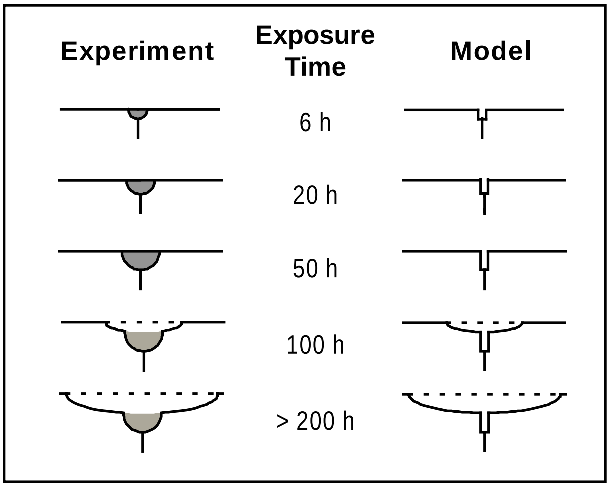

Figure 10: Model from Sharp *et al.*[15] of the development of exfoliation damage.

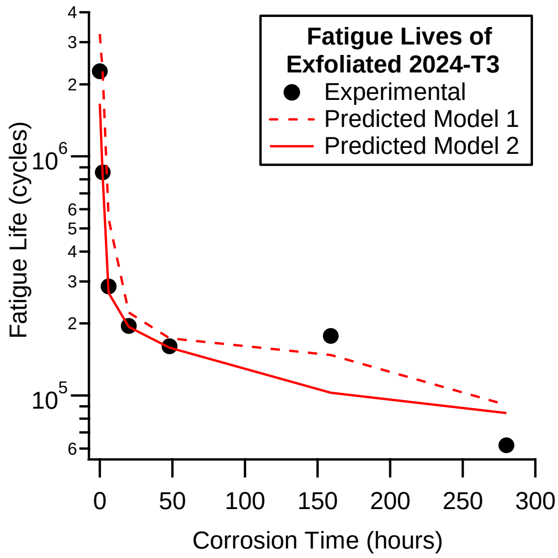

Figure 11: Predicted and measured 2024-T3 fatigue life vs. corrosion time using the process zone model.

3 Current Work

As can be seen, since 1997 DSTO has conducted a great deal of research into predicting the effects of prior corrosion on structural integrity. This research has mostly focused on specific problems in the RAAF fleet. DSTO is now (i) consolidating this work into a single database to facilitate its transfer into RAAF service and (ii) developing predictive models for other structurally significant modes of corrosion such as intergranular corrosion.

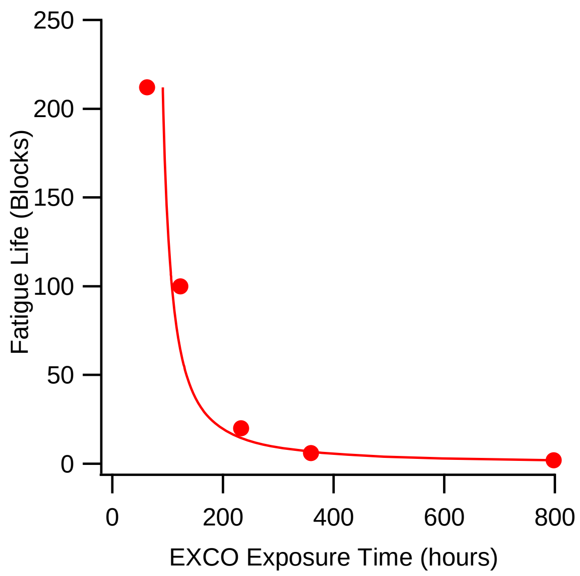

Figure 12: VA fatigue life versus EXCO exposure time. Specimens were tested using a Canadian C-130 Hercules spectrum.

3.1 Pitting Corrosion

3.1.1 Pitting Data Consolidation

As a result of it research, DSTO has collected a large amount of experimental data on the effect of pitting corrosion on the fatigue life and structural integrity of four alloys. Table 1 summarizes the numbers of corroded and uncorroded specimens tested in each of the project described in the previous section.

DSTO is now consolidating all of these data into a single database. This will allow the data to be analyzed as a whole. This is important as the 7010-T7651 and the 7050-T7651 projects used different pit metrics. Ideally, this would not be the case. Note, that D6ac will be excluded from this analysis as it was used only on the now-retired F-111. The consolidation of the data will also allow DSTO to share its dataset, where possible, with collaborators.

Table 1: Number of fatigue life tests for pitted and uncorroded specimens versus test material.

Research Project	Number of Test Specimens	
	Corroded	Uncorroded
D6ac Steel	65	0
7010-T7651	320	101
7050-T7451	24	8
7075-T6	11	11

3.1.2 Probabilistic modeling of low and high-k_t fatigue results for 7050-T7451

In addition to consolidating its current pitting corrosion data, DSTO is conducting a study of pitting corrosion in high and low-k_t fatigue specimens of 7050-T7451 corroded under the same conditions. This will allow results from low-k_t specimens to be used in high-k_t situations such as near a fastener hole. The high and low-k_t specimens have been machined in orientations that ensure that corrosion and fatigue crack growth occur in the same plane in both specimen types, Figure 13.

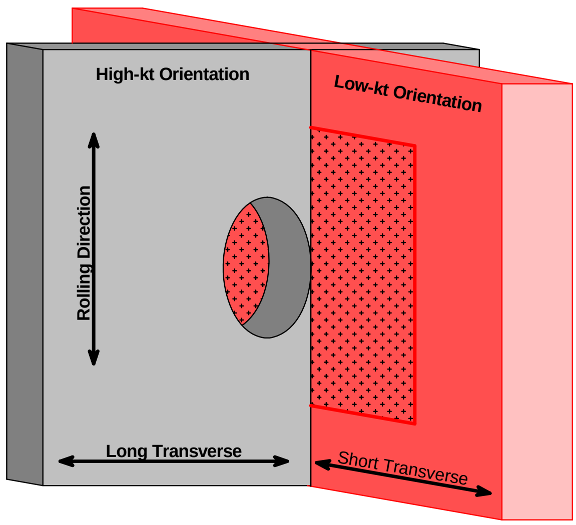

Figure 13: Comparison of the orientations of the high and low-k_t corrosion protocol specimens

As part of this study, the microstructure of the alloy will be characterized in detail and its fatigue crack growth rate behavior will be calculated from marker band measurements. These data will then be combined with the fatigue life results to develop a model using either AFGROW or FASTRAN of the effect of pitting corrosion on the fatigue life of the low-k_t specimens. A Monte-Carlo simulation (see Section 3.4) will be used to predict the fatigue behavior of the high-k_t specimens. The predictions of this model will then be compared with the experimental results from the high-k_t specimens. The goal is to determine if ECS models developed in low-k_t geometries can be used in high-k_t geometries, such as near fastener and open holes.

3.2 Intergranular Corrosion

DSTO is developing a model of how intergranular corrosion affects the fatigue life and structural integrity of the aluminum alloy 7075-T6, which is used in both the C-130 Hercules and the AP-3C Orion. Intergranular corrosion, exfoliation and stress corrosion cracking are common in this alloy due to its peak-aged temper.

One particular concern is the development of intergranular corrosion in the dome nut holes near the engine nacelles on the AP-3C. There is currently no quantitative way to estimate the structural significance of this corrosion. As a result, the RAAF has asked DSTO to develop a method for assessing the structural integrity impact of intergranular corrosion.

Given the above, DSTO is working with the RAAF to develop a means to quantify and model the effect of intergranular corrosion on the structural integrity of the dome nut holes. This work consists of (i) developing representative intergranular corrosion in the laboratory, (ii) fatigue testing of corroded specimens and (iii) developing a model of the effect of intergranular corrosion on fatigue life. At this stage DSTO has succeeded in simulating intergranular corrosion to a depth of 1.8 mm, see Figure 14. This is smaller than has been observed in service on the AP-3C. As a result, fatigue testing and modeling are yet to start.

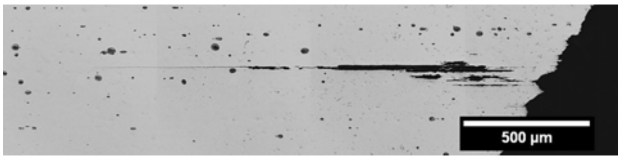

Figure 14: Optical micrograph showing intergranular corrosion near a hole in a sample of 7075-T6

3.3 Retrogression and Re-ageing

DSTO, in collaboration with the NRC of Canada, has been working on certifying the Retrogression and Re-ageing (RRA) heat treatment on RAAF aircraft, such as the C-130, since 2004. DSTO has now completed this certification effort and is awaiting design acceptance from the sponsor for this work. DSTO has shown that RRA can be performed reliably on components of extruded 7075-T6 of 6.35 to 25.4 mm thickness and up to 3.2 meter long.

RRA is discussed here as a successful example of technology transfer into RAAF service. In addition, DSTO are now conducting a trial of the use of RRA on the AP-3C Orion. This trial may lead to the certification of extruded 7075-T6 of less than 6.35 mm thickness.

3.4 Probabilistic Model of the Effect of Pitting Corrosion on Fatigue Life and Failure Location

The work described above, with the exception of RRA, has focused on the deleterious effects of various types of corrosion on fatigue life and structural integrity. Similarly, the literature has focused strongly in this area as well.

However, corrosion can also affect the locations at which fatigue failures occur. DSTO has undertaken a study of this location effect for pitting corrosion in 7010-T7651. This study used a Monte-Carlo simulation to predict how the location of fatigue failures in corroded low and high-k_t fatigue specimens differed from that in uncorroded specimens. The fatigue life predictions from this model are shown in Figure 15, which compares them to the fatigue life results from the 7010-T7651 project in which corrosion was centrally located. It also shows results from fatigue life specimens which were corroded at offset locations. The match between the experimental data and model predictions is very good except at the lowest stress level where there are some near-runouts, which have not been predicted by the model.

Figure 16 shows the model's predictions of the proportion of fatigue failures due to dual symmetric corrosion strikes versus the distances of these strikes from the middle of the specimen. This figure also shows the proportion of pit induced failures from an experimental trial of 16 specimens with symmetric dual corrosion strikes at 30 mm, 38 mm and 45 mm. There is good agreement between the results of the experimental trial and the modeling but the small size of the experimental trial means that this has limited statistical significance.

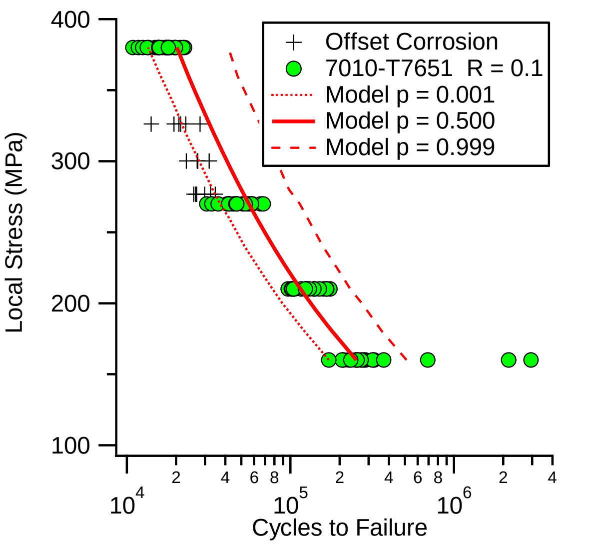

Figure 15: Comparison of fatigue life results from 7010-T7651 project with those obtained from the validation tests and those predicted by the Low-k_t Model

4 Transition to RAAF Service

DSTO has conducted a great deal of corrosion structural integrity research since 1997. The challenge now is to transfer this research into service. To do this DSTO is working with the RAAF to identify the modes of corrosion that are of the greatest concern. Currently these are intergranular and exfoliation corrosion in the AP-3C and pitting corrosion in the F/A-18. Therefore, DSTO is working with those maintaining these aircraft to transfer its models into service. DSTO is also working with the RAAF's airworthiness authority to add its models to the Environmental Degradation Management (EDM) toolbox. This will give the RAAF reliable and accurate models of how corrosion damage affects aircraft life, which will allow it to reduce it operating costs.

5 Conclusion

DSTO has developed a set of accurate models that can predict the reduction of fatigue life and structural integrity in aircraft structural alloys. This includes models for pitting and exfoliation corrosion while work has begun on a model for intergranular corrosion. The challenge now is to transfer these models into service on RAAF aircraft. DSTO is therefore developing technology transfer plans, based on its experience in certifying RRA for use on the C-130, to transfer its models for pitting and intergranular corrosion into service on relevant aircraft. The overarching goal is to reduce the operating cost of the RAAF fleet while increasing its operational availability.

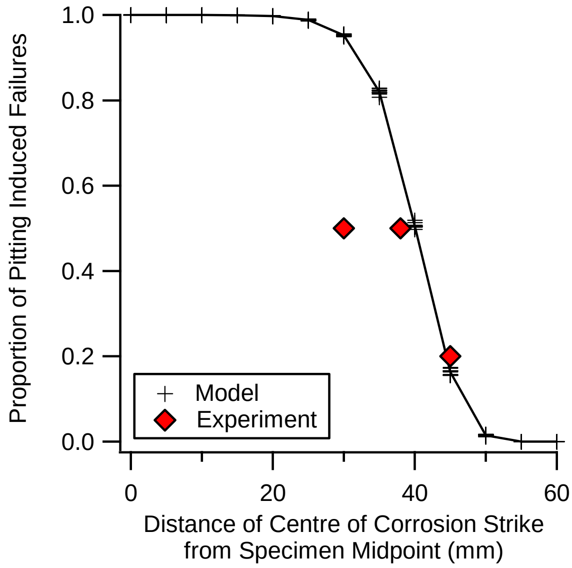

Figure 16: Proportion of failures due to pitting for single and dual symmetric corrosion strikes vs. distance from the midpoint of the specimen. σ_{max} = 380 MPa, R = 0.1 and each data point represents 5,000 replicates.

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