Chapter 5 – PITTING CORROSION: MORPHOLOGY AND CHARACTERIZATION

David W. Hoeppner
Professor and Director, Quality and Integrity Design Engineering Center (QIDEC)
Mechanical Engineering Department, University of Utah
Salt Lake City, Utah
USA

5.1 INTRODUCTION

Pit formation is a concern for integrity of components of aircraft for many reasons as cited in Chapter 13. Pits not only form local discontinuities (MDS – Modified Discontinuity States) but also serve as the nucleus of cracks under both sustained loading and cyclic loading of structural components.

In corrosion fatigue conditions, several studies have shown greater increase in fatigue crack growth rates compared to "baseline" fatigue conditions. Although major efforts have been expended to understand the crack propagation behavior of materials, a few studies have focused on the crack nucleation stage in the overall fatigue process. McAdam first suggested that corrosion induced pits might act as stress concentrators from which cracks could form [1]-[3]. A large number of chemical or electrochemical factors such as potential, passive film, pH, and composition of environment are found to affect the pitting corrosion fatigue process. As well, mechanical factors such as stress range, frequency, stress ratio (R), load waveform and metallurgical factors such as material composition, microstructure, heat treatment, and grain orientation can influence pitting corrosion fatigue processes. Nucleation of cracks from corrosion pits was observed by many researchers [1]-[19] including the works of Hoeppner [20]-[21], McAdam [22], and Goto [23] in heat-treated carbon steel, and Muller [24] in several steels. As well, in NaCl environment, lowering of the fatigue life due to the generation of pits in carbon steel [21],[22] and 7075-T6 Aluminum alloy [6],[21] was observed under corrosion fatigue conditions.

Once the pit forms, the rate of pit growth is dependent mainly on the chemical composition of the material, the microstructure of the material, temperature, duration of attack, local solution conditions, and the state of stress. Cracks have been observed to form from pits under cyclic loading conditions. Therefore, to estimate the total corrosion fatigue life of a structural component made of a given material it is of great importance to develop some realistic models to establish the relationship between pit propagation rate and the state of stress. This will also be discussed in Chapter 13. Furthermore, pitting corrosion in conjunction with externally applied mechanical stresses, for example, cyclic stresses, has been shown to severely affect the integrity of the oxide film as well as the fatigue life of a metal alloy. To understand and estimate the effects of pitting as well as to formulate repair procedures on components where pitting corrosion has been detected it is necessary to be able to characterize the pits.

5.2 PITTING CORROSION

Pitting is a form of localized corrosion that proceeds because of local cell action once the pitting potential has been attained under a given set of conditions for a given material in a given chemical environment. It is involved in causing serious integrity concerns related to several of the items noted above.

The autocatalytic reaction involved in pitting corrosion produces cavities/EDS (Evolving Discontinuity States) beginning at the surface and taking a myriad of shapes and sizes depending on both the microstructure of the material and the electrolyte and various electrochemical factors. One of the items to be dealt with in this chapter is the importance of attempting to characterize pitting corrosion. This needs to

be done in order to evaluate the requirement for removal of pitting once it is discovered, to analyze the significance of it in a corrosion and corrosion fatigue design system and to assure safety can be maintained even if pits of a certain character are present but not found in non-destructive inspection for one reason or another.

Temperature and time of exposure are critical parameters involved in the thermodynamics and kinetics of pitting corrosion. The cavities/EDS that form may or may not become filled with corrosion products. Pitting processes often proceed in growth by a combination of both intergranular attack and dissolution of the pit "walls". As the pits are evolving they are referred to as Evolving Discontinuity States (EDS). If the process is fixed at time t the state is referred to as a Modified Discontinuity State (MDS). The characterization of both the EDS and the MDS has been of concern to scientists and engineers since the study of pitting corrosion began.

Pitting occurs when an electrolyte begins to allow the transport of ions between an anode and cathode. Only a small amount of metal is corroded and this is usually referred to as localized attack. The anticipation of pitting on structural members is a critical factor in maintaining component integrity and safety in some cases.

Inspection and characterization of pits in laboratories and in field applications is a challenging endeavor. This is done to establish the shape and general morphology of pits and to establish their surface dimensions and shape. Pit depths can be measured using a calibrated microscope focused first on the top of the pit and then on the bottom of the pit. More discussion of characterization of pits will follow.

Efforts have been made to treat the rate of corrosion pitting penetration into materials statistically. All the models known to date involve expressions for depth or area of pits, thus emphasizing the need for characterization. For example, equations have been developed to predict the perforation of boiler tubes, buried steel pipelines, critical components of aircraft and related areas. There is much work underway on pitting in both power plants and pipelines at present. The characterization of pitting has been of major concern to various types of power plants for many years.

In the airframe (both fixed wing and rotary wing) and aero-engine industry pitting has been recognized as a potential safety issue for some time and produces obvious maintenance concerns. Until recently both USAF and the USA FAA did not consider pitting or other mechanisms of corrosion as safety concerns. Since the Aloha Airlines accident of 1988 this has changed and in 1998 the FAA started requiring design for corrosion as a threat to structural integrity. However, most companies and government agencies are still in the embryonic stage with regard to design for pitting corrosion and similar threats. In addition, the USAF is in the process of modifying Mil Handbook 1530 to include corrosion as a consideration in design for structural integrity.

The efforts of Bob Jeal and David Hoeppner in moving toward a HOLISTIC Structural Integrity design framework (1985) [25],[26] has influenced some companies and government agencies to move toward a HOLSIP framework. The Canadian Department of National Defence (DND), led by efforts at NRC-IAR, has done an extensive amount of work to establish methods for characterizing corrosion and developing models to validate its prediction on aircraft structures. In addition, the British Royal Navy and Air Force through their ESVRE (Establish, Sustain, Validate, Recover, Exploit; ES<Air> Structures Support Group – UK) has implemented tools to design for corrosion effects in structural integrity and to maintain aircraft structures through their program. JAXA (the Japanese Aerospace Laboratory) and the Japanese equivalent to the USA Occupational Health and Safety efforts have begun implanting design for corrosion. Many of the activities mentioned are discussed in annual HOLSIP (Holistic Structural Integrity Processes) meetings that have been held since 2002. (See www.holsip.com). These organizations as well as AP/ES, and the University of Utah have done much research on attempting to characterize pits and incorporate them into models.

It has been shown that the rate of penetration of pits in aluminum exposed to water follows a cube root curve. The following equation represents Godard's model:

$$d_{max.} = C(t)^{1/3} \tag{1}$$

where: d = maximum pitting depth

t = time

C = a parameter related to the combination of material and environment

The importance of an expression such as that above is that it provides a means of estimating the depth of pits from knowledge of the time of exposure. Thus it is very useful in models to estimate the significance of corrosion pits in affecting structural integrity. The use of this expression is discussed more in Chapter 13. A diagram depicting how this equation usually plots from data is shown below in Figure 5-1.

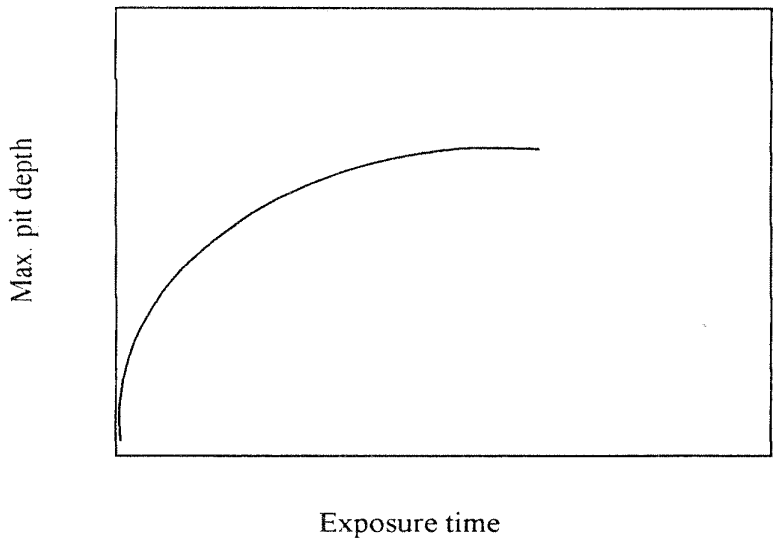


Figure 5-1: Schematic Diagram Showing the Relationship Between Penetration Depth and Exposure Time.

Equations incorporating the model above have been used extensively in models for pitting corrosion fatigue as will be discussed in a later section of this report. The greatest challenge in using the expression above, or similar ones, is in determining the pit depth. A brief discussion of how this pit characterization has been attempted is presented below. In attempting to detect corrosion pits and characterize their size and shape many approaches have been used.

5.2.1 Pit Characterization

Early workers studying pitting used various optical techniques to attempt to characterize pits. It became clear that this was not acceptable since it was virtually impossible to capture the depth and complex shape of pits below a surface. Optical techniques did prove useful for area determination related to surface area. But it was recognized by most researchers that the most important parameter related to assessing pit criticality was the depth. This dimension also is used extensively in maintenance for corrosion and rework considerations. Thus, in recent years more emphasis has been placed on developing methods of determining pit depth and shape. The following methods have been more extensively used in recent years:

1) Sectioning;
2) Replication and examination in scanning electron microscopes;
3) Examination of pit profiles subsequent to fracture or sectioning;
4) Use of confocal microscopy; and
5) Eddy current probes of various types.

Obviously any destructive technique on actual components is not that useful. Thus some rework or "blend" methods suggest or require attempting to use visual or other NDI as corrosion pits are blended out and then specifying a depth for additional removal of material to assure any remaining pit induced degradation will also be removed.

In research at the University of Utah over the last 25 years confocal microscopy has proved the most useful to determine pit depth, and pit shape to some extent, but does require observation in a laboratory setting. Thus it is not useful for field use at present. Many challenges with respect to evaluation of the threat of pitting to structural integrity arise in the field after pits have either caused a major failure or have been detected in areas of components where they were not expected and were not considered in the original structural integrity evaluation. The determination of pit depth remains a great challenge in these situations.

The ASTM G46[1] Standard Guide for the "Examination and Evaluation of Pitting Corrosion" is one of the most advanced descriptions of how to characterize pitting. This is one of the major starting points for all those interested in characterizing, evaluating and modeling pitting corrosion. The ASTM standard G15[2] entitled "Standard Terminology Relating to Corrosion and Corrosion Testing" is important to obtain and use in characterizing pitting corrosion as well as all forms of corrosion. Figure 5-2 below shows how pits may be classified by density, shape and size in the standard. In addition, Figure 5-3 shows the cross-sections and the variation according to the standard G46. The Advisory Circular AC 43-4A also has a way to classify pits [27]. However it tends to be very qualitative in nature and tends to concentrate on repair of pitting as well as other corrosion mechanisms. The document classifies pitting as **light** when at a depth of 0.025 mm (0.001 inch) maximum. Moderate pitting is viewed as potentially 0.25 mm (0.010 inch) and notes this type of damage is usually removed by "extensive mechanical sanding". It does little to clarify what "extensive mechanical sanding" is and how deep or extensive it must be done. Pages 124-5 of reference 27 do state some guidelines but don't emphasize the issue of characterizing pitting corrosion [28]. One of their statements is that the "pit has been cleaned up to the extent that all loose corrosion products have been removed". Of course they do not mention the important issue of tunneling often connected with pits and the issue of intergranular attack and cracking that occurs with pit formation. Thus, due diligence must be exercised when removing by blending and sanding to "eliminate" pits. Much more effort must be expended on characterizing pits by NDI methods such as eddy current techniques or others in order to assure all traces of corrosion pitting degradation have been eliminated.

[1] ASTM Standard G46, Guide for the Examination and Evaluation of Pitting Corrosion, AMERICAN SOCIETY FOR TESTING AND MATERIALS, 100 Barr Harbor Dr., West Conshohocken, PA, USA, Approved on a regular basis.

[2] ASTM Standard G15, Standard Terminology Relating to Corrosion and Corrosion Testing, AMERICAN SOCIETY FOR TESTING AND MATERIALS, 100 Barr Harbor Dr., West Conshohocken, PA, USA, Approved on a regular basis.

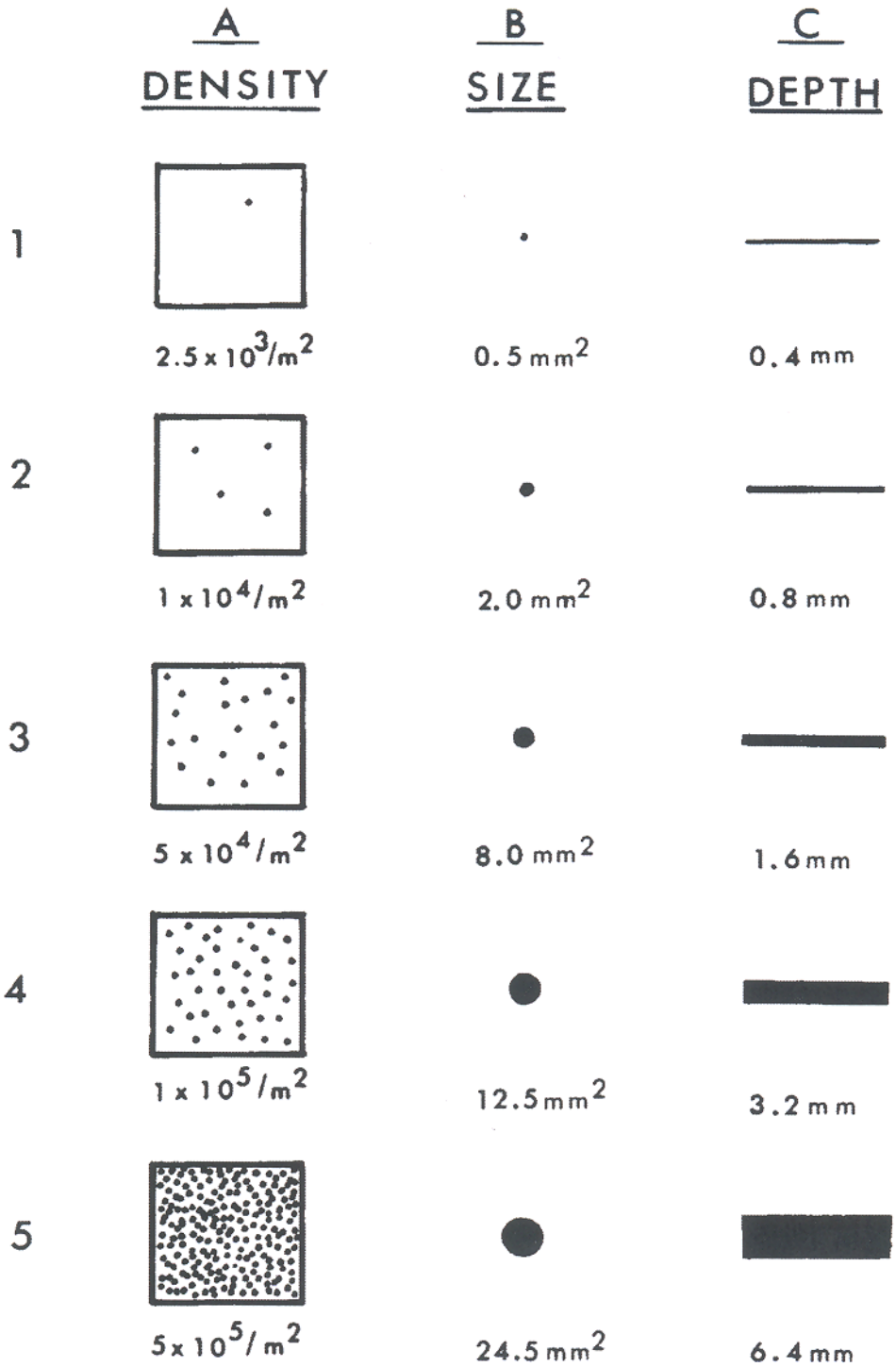


Figure 5-2: ASTM Standard G46 Showing Means of Characterizing Pit Density, Size, and Depth (Copyright ASTM).

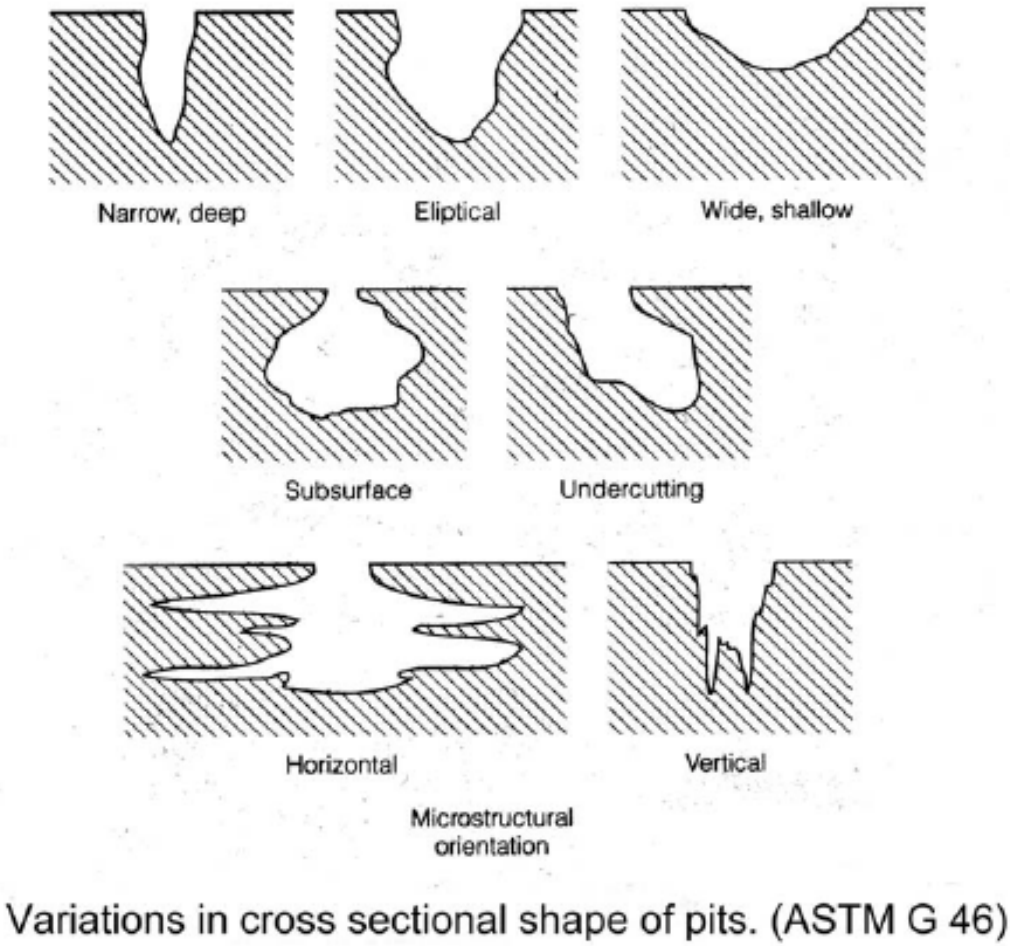


Figure 5-3: ASTM Standard G46 Portion Showing Variation of Pit Character (Copyright ASTM).

5.2.2 Examples of Pitting Encountered in Components

In the design of aircraft, damage due to corrosion mechanisms, and especially pitting, has not been considered as a criterion for determining either Structurally Significant Location (SSL) or Structurally Significant Items (SSI). Although most airframes, and power plants, have a Corrosion Prevention and Control Program (CPCP) they are designed for integrity under either the safe life or damage tolerant paradigms. Neither of these has considered corrosion in a critical way other than to use a CPCP. Thus stress or damage related allowables are generally not available for the various corrosion mechanisms. For example, if one were to query what the corrosion or corrosion fatigue pitting allowable is for a given component it would not likely be available. This is unfortunate since if corrosion pitting is found the only alternative becomes a repair to attempt to remove all of the pitting even though that is difficult on many occasions. The CPCP approach has provided some measure of protection and control but has proved to be inadequate. For this reason corrosion often is detected by diligent maintenance personnel or it becomes a recognized problem only when a failure has occurred in areas of components where it was not anticipated. Inspections often are “of opportunity” and neither quantified nor directed for corrosion. The issue of directed NDI (Non-Destructive Inspection) does occur after a problem has been identified by one means or another. In order to quantify and direct the inspections the following must be specified and placed in the maintenance manuals to some degree:

1) An indication of the **exact type of corrosion** being looked for should be specified. (What to look for!)

2) The **location** which is to be inspected must be clearly spelled out. (Where to look!)
3) The specific inspection **equipment** and **method** should be specified. (How to look!)
4) Either the **time of use or flight cycles** or both should be specified in order to specify when to look.
5) The **frequency** of inspections and time between inspections should be specified. (Repeat inspection interval for corrosion-how often to look)
6) The **detection threshold** for the type of corrosion should be specified.
7) The **Probability Of Detection** (POD) for the type of corrosion should be specified.

In the case of pitting corrosion the items above often are not defined until an accident, an incident, or an unexpected detection has occurred and is viewed as critical to safety. At that point the above often have been defined. In addition, detailed repair procedures often are developed at that point as well.

The following is an example of unexpected pitting corrosion on a “non-critical component” detected in service. The C130 aircraft, used in many countries throughout the world, was found to have cracking in a fitting that is in the rear of the aircraft and is referred to as either the “Porkchop” fitting or the “hockey stick fitting”. Which reference is used is a function of the country in which the problem was discovered. Some indicated the problem was due to stress corrosion. This is not viewed likely since the component experiences cyclic loads. When both DND, Canada, and the New Zealand forces were experiencing cracking of the component they decided to have competent failure analysis labs evaluate the cracked fittings further. Thus, the Aerospace and Maritime Research Laboratory (AMRL) in Melbourne, Australia and the Quality Engineering Test Establishment (QETE) in Gatineau, Quebec, Canada performed failure analyses on the subject components. Additional failure analysis was done by the University of Utah Quality and Integrity Design Laboratory (QIDEC) and IAR (Institute of Aerospace Research) in Ottawa, Ontario, Canada. Figure 5-4 and Figure 5-5 show two views of the pits that nucleated the fatigue cracks. In addition, growth rings typical of fatigue, in this case most likely environmentally assisted fatigue crack propagation, are also clearly apparent. AMRL and QETE were both helpful in identifying the true failure mode in this case. The subject component had not been identified as a structurally significant item. The cracking was found initially by diligent maintenance personnel. Subsequent to the discovery of the corrosion pitting as the source of the cracks a program was put into place to monitor the area in question for corrosion thereby preventing the rampant formation of both corrosion pits and fatigue cracking. This was a significant aid to all the forces flying this particular transport aircraft.

Figure 5-4: Fracture Surface of C130 "Porkchop" Fitting that Unexpectedly Failed from Pitting that Transitioned into Cracks.

(Photo by Ms. Amy Taylor, and David W. Hoeppner, University of Utah, 1999. Crack started at a pit at the lower right corner and propagated by corrosion fatigue mechanisms. This was commonly observed.)

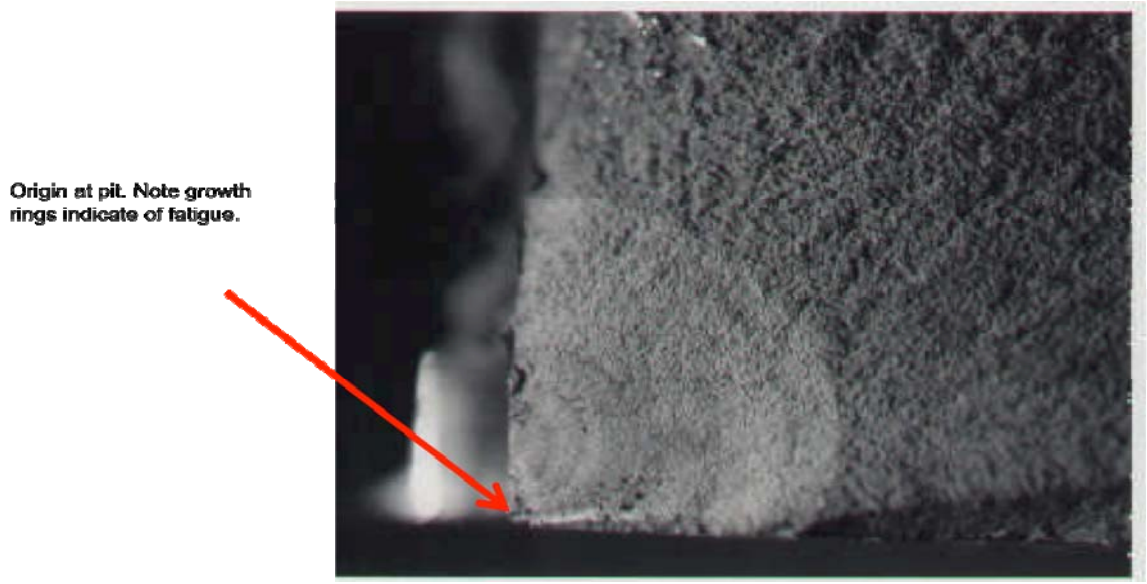


Figure 5-5: A Second View of the Fracture Surface of C130 "Porkchop" Fitting that Unexpectedly Failed from Pitting that Transitioned into Cracks.

(Photo by Ms. Amy Taylor, and David W. Hoeppner, University of Utah, 1999. In this view the crack nucleated at the lower left corner at a pit and propagated by corrosion fatigue. Note the growth rings as the crack propagates from the lower left toward the upper right corner of the photograph.)

Figure 5-6 and Figure 5-7 above show, respectively, the formation of fatigue cracks at corrosion pits and how fatigue cracks are observed to link pitting. It has been known for some time that both these occur. Thus, corrosion pitting often creates multiple site damage. The characterization studies done recently at the UU QIDEC laboratories have been instrumental in identifying features of pitting that are useful in modeling (see Chapter 7 and references [27]-[49]).

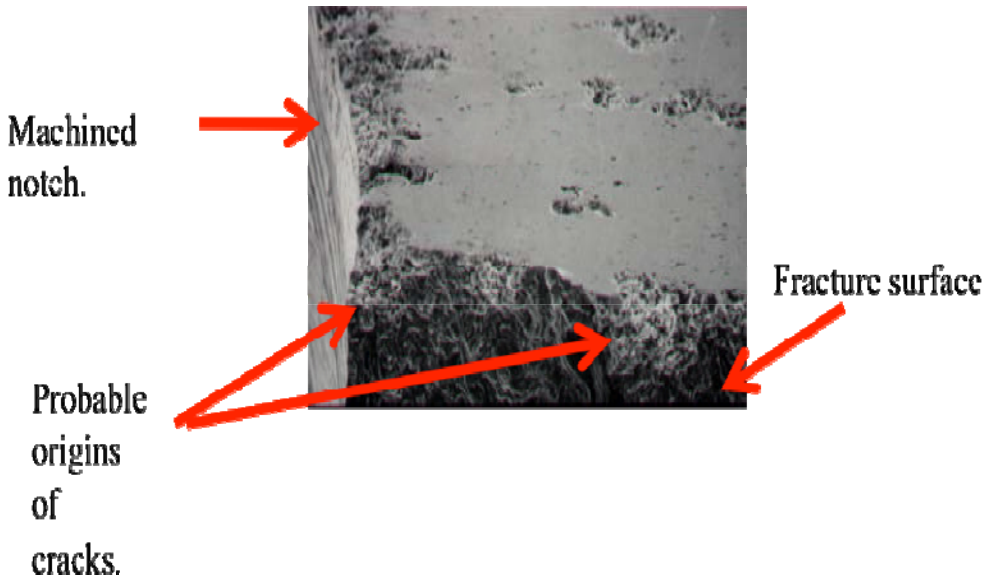


Figure 5-6: View Showing Corrosion Pits Nucleating Cracks.

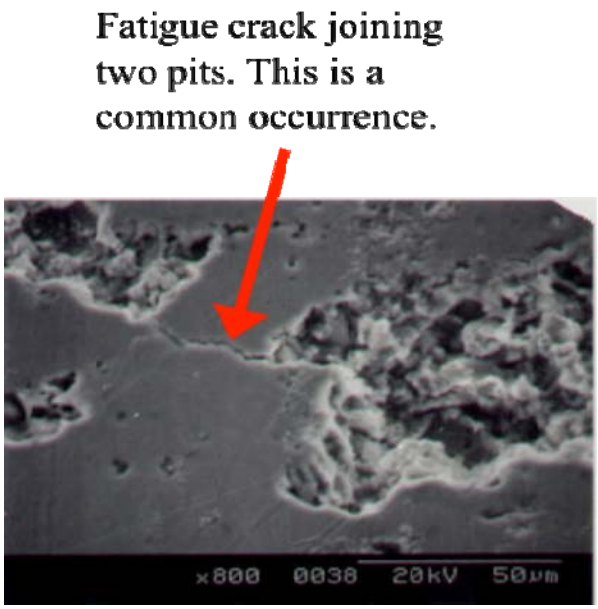
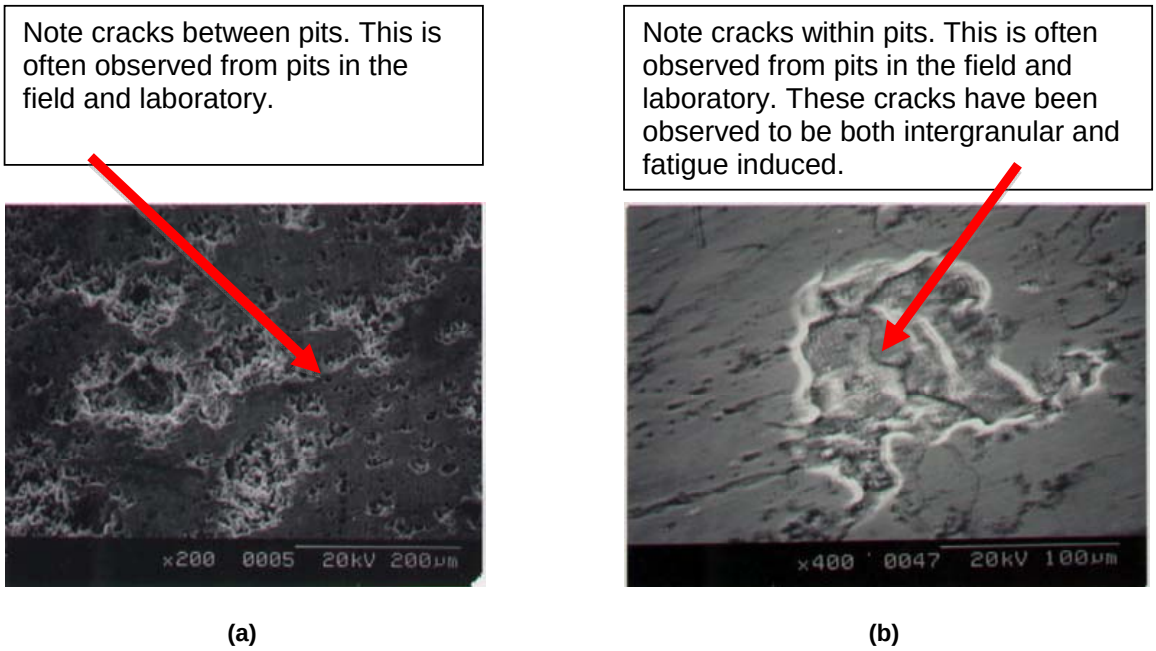


Figure 5-7: View Showing Other Pits with Fatigue Cracks Propagating Between Them.

Figure 5-8(a) below shows the frequently observed occurrence of either sustained load or cyclic load induced cracks forming and linking pits. This has significant implications in formulating repair practices and in developing acccurate models to predict corrosion pit growth rates and incorporating them into

models. On the other hand Figure 5-8(b) shows a view of cracks in the bottom of pits. This observation was made quite frequently. (Although not visisble in this photo cracks also were observed in pit walls. This too was frequently observed).



(a) **(b)**

Figure 5-8: Views in the Notch of Corrosion Fatigue Specimens Tested in the QIDEC Laboratory at the University of Utah (2000). Alloy was 7075-T6 tested in 3.5% salt water.

Figure 5-9 below shows an example of an image of pits taken in a confocal microscope. The confocal microscope has been very successful in allowing the determination of pit depth and more clarity on the shape of pits as well (see Ref. [49] for more general descriptions of the use of the confocal microscope to characterize pits. This is in additon to many other references cited herein). Another example of the characterization of pits is shown in Figure 5-10. In this case the confocal microscope was used in conjunction with the SEM (Scanning Electron Microscope) to characterize the depth and shape of corrosion pits developing under corrosion fatigue test conditions. These tools proved invaluable in their ability to assist in characterizing the depth and shape for use in modeling efforts as described in Chapter 7 of this report.

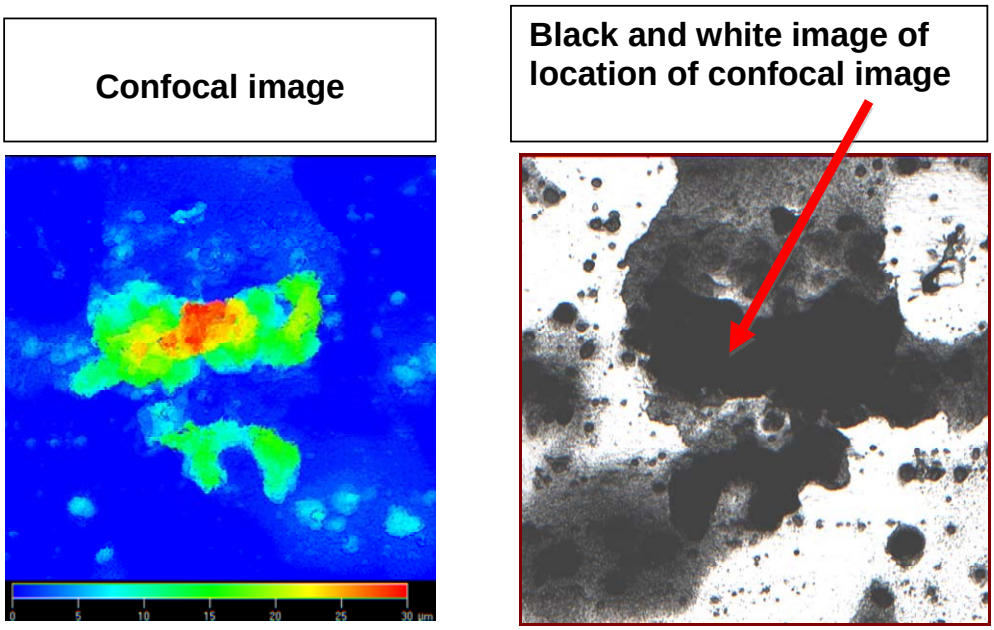
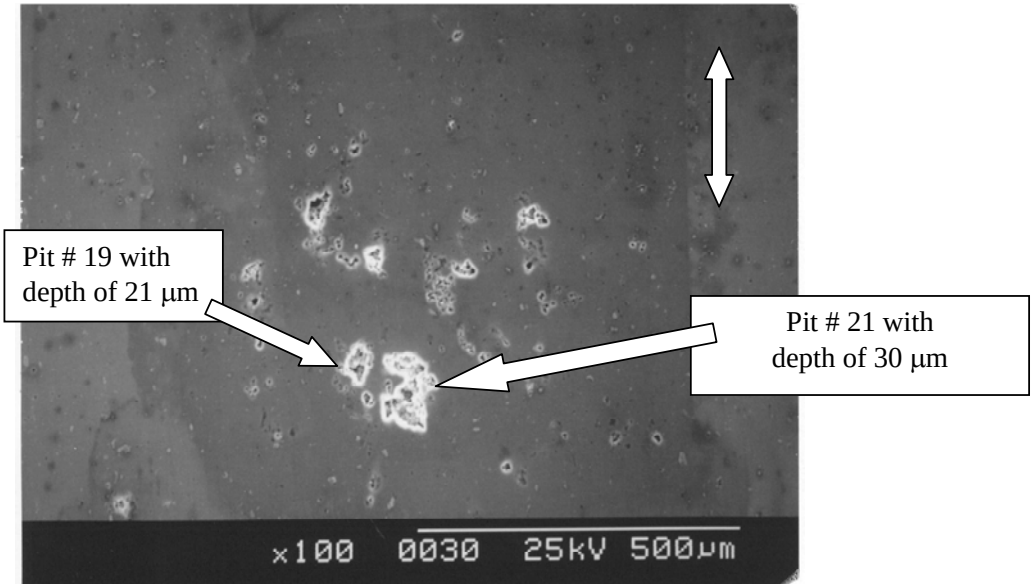
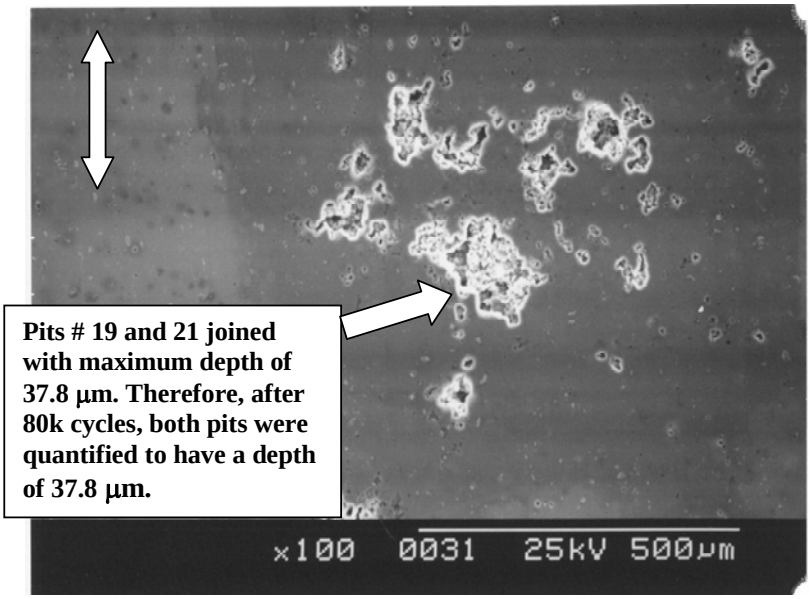


Figure 5-9: Post Corrosion Exposure of 30 Hours, d~0.0012" (30 mm) of Pit: Left image shows typical confocal image with variation in color showing depth – red indicates the deepest area of the pit; Image on right shows area where confocal image was taken.



(a)



(b)

Figure 5-10: SEM Photos Showing Pits Developed Under Corrosion Fatigue Conditions: (a) After 60,000 Cycles; and (b) After 80,000 Cycles. Vertical arrows indicate loading direction. Depth of pits determined by confocal microscopy. (Material was 7075-T6 tested in ASTM 3.5% NaCl solution).

5.3 CONCLUDING REMARKS

This chapter has described various techniques for characterizing pitting corrosion. Pitting has been observed to occur much more frequently than envisioned in early design of critical components of fixed wing and rotary wing aircraft. In some cases it has proved fatal due to lack of its consideration in the original design and lack of an ability to characterize it once it has been observed to occur. Some repair/

blend/sanding techniques are commonly used in maintenance to attempt to eliminate pitting. This in a sense has avoided the critical task of attempting to characterize pitting corrosion in terms of both depth and shape, and particularly shape below a surface. Thus, even though some NDI techniques have been used to attempt to assure that all detected pitting has been removed once it has been found in critical areas on critical components, much more work on quantification of NDI procedures to both detect pitting and completely characterize it are needed. In addition, much more exploration and quantification of NDI for pitting corrosion detection is needed. This included definition of the detection thresholds of various NDI practices for use in maintenance and original design. In addition, the probability of detection for various NDI practices employed to characterize pits also must be determined and included in both as well.

Another issue that is greatly needed in the future is the education of engineering students to deal with all types of corrosion on aircraft including pitting corrosion. This field has been sorrowfully neglected by the aviation industry in terms of going beyond the typical CPCP (Corrosion Prevention and Control Program). Some progress in this later area has been made but the engineering schools throughout the world still do not include enough education on corrosion and how to design for its occurrence (this is true of almost all designs and not just aircraft). The continued development of the HOLSIP concepts (Holistic Structural Integrity Design Processes) are providing much guidance on how to deal with all the issues mentioned.

5.4 REFERENCES

[1] McAdam, Jr., D.J., “Stress-Strain-Cycle Relationship and Corrosion-Fatigue of Metals”, Proceedings of the ASTM, Vol. 26 (II), pp. 224-280, 1926.

[2] McAdam, Jr., D.J., “Corrosion-Fatigue of Non-Ferrous Metals”, Proceedings of the ASTM, Vol. 27 (II), pp. 102-152, 1927.

[3] McAdam, Jr., D.J., “Corrosion Fatigue of Metals Under Cyclic Stress”, Proceedings of the ASTM, Vol. 29, No. 2, pp. 250-313, 1929.

[4] Pettit, D., Ryder, J., Krupp, W. and Hoeppner, D., “Investigation of the Effects of Stress and Chemical Environments on the Prediction of Fracture in Aircraft Structural Materials”, AFML-TR-74-183, Lockheed California Company, December 1974.

[5] Aging of U.S. Air Force Aircraft, National Research Council (NRC) National Materials Advisory Board (NMAB) Report, National Academy Press, Washington, DC, USA, 1997.

[6] Cole, G.K., Clark, G. and Sharp, P.K., “The Implications of Corrosion with Respect to Aircraft Structural Integrity”, DSTO-RR-0102, DSTO, Melbourne, Victoria, Australia.

[7] Groner, D.J., “US Air Force Aging Aircraft Corrosion”, Current Awareness Bulletin, Structures Division, Wright Laboratory, Spring 1997.

[8] Piascik, R.S., Kelly, R.G., Inman, M.E. and Willard, S.A., “Fuselage Lap Splice Corrosion”, WL-TR-96-4094, Vol. II, ASIP, 1996.

[9] Mills, T.B., “The Combined Effects of Prior Corrosion and Aggressive Chemical Environments on Fatigue Crack Growth Behavior in Aluminum Alloy 7075-T651”, Ph.D. Dissertation, University of Utah, 1997.

[10] Mills, T.B., “The Effects of Exfoliation Corrosion on the Fatigue Response of 7075-T651 Aluminum Plate”, M.S. Thesis, University of Utah, 1994.

[11] Chubb, J.P., Morad, T.A., Hockenhull, B.S. and Bristow, J.W., "The Effect of Exfoliation Corrosion on the Fatigue Behavior of Structural Aluminum Alloys", in Structural Integrity of Aging Airplanes, pp. 87-97, 1991.

[12] Pettit, D.E., Ryder, J.T., Krupp, W.E. and Hoeppner, D.W., "Investigation of the Effects of Stress and Chemical Environments on the Prediction of Fracture in Aircraft Structural Materials", AFML-TR-74-183, 1974.

[13] Swartz, D.D., Miller, M. and Hoeppner, D.W., "Chemical Environments in Commercial Transport Aircraft and Their Effect on Corrosion Fatigue Crack Propagation", in Estimation, Enhancement and Control of Aircraft Fatigue Performance, Vol. I, J.M. Grandage and G.S. Jost, Eds., The proceedings of the 14th Symposium of the International Committee on Aeronautical Fatigue, Melbourne, Victoria, Australia, pp. 353-364, 3-5 May 1995.

[14] Kramer, J. and Hoeppner, D.W., "Effects of Cyclic Immersion in 3.5% NaCl Solution on Fatigue Crack Propagation Rates in Aluminum 2024-T351", Proceedings of the 1995 USAF Structural Integrity Program Conference, WL-TR-96-4093, Vol. II, pp. 1089-1112, 1995.

[15] Mills, T.B., Magda, D.J., Kinyon, S.E. and Hoeppner, D.W., "Fatigue Crack Growth and Residual Strength Analyses of Service Corroded 2024-T3 Aluminum Fuselage Panels", Report to Oklahoma City Air Logistics Center and Boeing Defense and Space Group, University of Utah, 1995.

[16] Komorowski, J.P., Bellinger, N.C. and Gould, R.W., "The Role of Corrosion Pillowing in NDI and in the Structural Integrity of Fuselage Joints", in Fatigue in New and Aging Aircraft, Proceedings of the 19th Symposium of ICAF, 1997.

[17] Op-cit Ref. 12.

[18] Bellinger, N.C., Komorowski, J.P. and Gould, R.W., "Damage Tolerance Implications of Corrosion Pillowing on Fuselage Lap Joints", Journal of Aircraft, Vol. 35, No. 3, pp. 487-491, May – June 1998.

[19] Bellinger, N.C. and Komorowski, J.P., "Corrosion Pillowing Stresses in Fuselage Lap Joints", AIAA Journal, Vol. 35, No. 3, 1997.

[20] Hoeppner, D.W., Mann, D.S. and Weekes, J., "Fracture Mechanics Based Modeling of Corrosion Fatigue Process", in Corrosion Fatigue: Proceedings of the 52nd meeting of the AGARD Structures and Materials Panel held in Turkey, 5-10 April 1981.

[21] Hoeppner, D.W., "Corrosion Fatigue Considerations in Materials Selections and Engineering Design", Corrosion Fatigue: Chemistry, Mechanics, and Microstructure, NACE, pp. 3-11, 1972.

[22] McAdam, D.J. and Gell, G.W., "Pitting and its Effect on the Fatigue Limit of Steels Corroded Under Various Conditions", Journal of the Proceedings of the American Society for Testing Materials, Vol. 41, pp. 696-732, 1928.

[23] Goto, M. and Nisitani, H., "Crack Initiation and Propagation Behavior of a Heat Treated Carbon Steel in Corrosion Fatigue", Fatigue Fracture Engineering Material Structure, Vol. 15, No. 4, pp. 353-363, 1992.

[24] Muller, M., "Theoretical Considerations on Corrosion Fatigue Crack Initiation", Metallurgical Transactions, Vol. 13A, pp. 649-655, 1982.

[25] Jeal, R.H., "Damage Tolerance Concepts for Critical Engine Components", Invited Keynote Paper, AGARD Conference, San Antonio, Texas, April 1985, Published in Conference Proceedings AGARD-

CP-393, Damage Tolerance Concepts for Critical Engine Components, Invited Keynote Paper, pp. 1-1 to 1-12, October 1985.

[26] Hoeppner, D.W., "Parameters that Input to Application of Damage Tolerance Concepts to Critical Engine Components", AGARD Conference, San Antonio, Texas, April 1985, Published in Conference Proceedings AGARD-CP 393, Damage Tolerance Concepts for Critical Engine Components, Invited Keynote Paper, pp. 4-1 to 4-16, NATO-AGARD, France, October 1985.

[27] "Corrosion Control of Aircraft", AC 43-4A, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, USA, p. 151, 1991.

[28] Op. Cit. Ref. 27, pp. 124-125.

[29] Jones, K. and Hoeppner, D.W., "The Interaction Between Pitting Corrosion, Grain Boundaries, and Constituent Particles During Corrosion Fatigue of 7075-T6 Aluminum Alloy", International Journal of Fatigue, Vol. 31, pp. 686-692, February 2009.

[30] Jones, K. and Hoeppner, D.W, "Prior Corrosion and Fatigue of 2024-T3 Aluminum Alloy", Corrosion Science, Vol. 48, No. 10, pp. 3109-3122, 2006.

[31] Jones, K., Shinde, S.R., Clark, P.N. and Hoeppner, D.W., "Effect of Prior Corrosion on Short Crack Behavior in 2024-T3 Aluminum Alloy", Corrosion Science, Vol. 50, Issue 9, pp. 2588-2595, September 2008.

[32] Clark, P.N., Jones, K., Huang, J.T. and Hoeppner, D.W., "Observations from the Inspection of an Aged Fuselage Panel", Journal of Aircraft, Vol. 42, No. 6, pp. 1403-1408, 2005.

[33] Clark, P.N., Jones, K., Huang, J.T. and Hoeppner D.W., "Observations from the Inspection and Sectioning of an Aged Fuselage Panel", Proceedings, USAF Aircraft Structural Integrity Program (ASIP) Conference, December 2002.

[34] Clark, P.N., Jones, K. and Hoeppner, D.W., "Pitting Behavior and Residual Fatigue Life of 7075-T6, Aluminum Extruded C-141 Wing", Proceeding, International Committee on Aeronautical Fatigue (ICAF) Lucerne, Switzerland, 2003.

[35] Okada, T. and Hoeppner, D.W., "The Behavior of Short Cracks in Corrosive Environments for 7075 Al Alloy", Presented at ICAF 2005, Hamburg, Germany, 2005, ICAF 2005 – Structural Integrity of Advanced Aircraft and Life Extension for Current Fleets – Lessons Learned in 50 Years after the Comet Accidents, Vol. 2, Edited by Claudio Dalle Donne, Proceedings, 23rd Symposium of the International Committee on Aeronautical Fatigue, pp. 613-622, 2005.

[36] Jones, K. and Hoeppner, D.W., "Pitting Corrosion, Grain Boundaries, and Constituent Particles: Which One Will Win the Crack Nucleation Race", Presented at the International Committee of Aeronautical Fatigue Meeting, Hamburg, Germany, ICAF 2005 – Structural Integrity of Advanced Aircraft and Life Extension for Current Fleets – Lessons Learned in 50 Years after the Comet Accidents, Vol. 2, Edited by Claudio Dalle Donne, Proceedings of the 23rd Symposium of the International Committee on Aeronautical Fatigue, June 2005.

[37] Jones, K. and Hoeppner, D.W., "Pit-to-Crack Transition in Prior-corroded 2024-T3 Aluminum Alloy Under Cyclic Loading", Corrosion Science, pp. 2185-2198, 2005.

[38] Jones, K. and Hoeppner, D.W., "Effect of Microstructure on Pit-to-Crack Transition of 7075 T6 Aluminum Alloy", Fatigue and Fracture Mechanics, ASTM STP 1480, R.E. Link and K.M. Nikbin

(Eds.), American Society for Testing and Materials International, Mayfield, PA, USA, pp. 271-280, 2008.

[39] Jones, K. and Hoeppner, D.W., "Pit-to-Crack Transition in Prior-Corroded 2024-T3 Aluminum Alloy under Cyclic Loading", Corrosion Science, Vol. 48/10, pp. 3109-3122, 2006.

[40] Hoeppner, D.W., "A Review of Corrosion Fatigue and Corrosion/Fatigue Considerations in Aircraft Structural Design", Invited Paper Presented at International Conference on Fatigue of Aircraft, Lucerne, Switzerland, May, 2003, ICAF 2003 – Fatigue of Aeronautical Structures as an Engineering Challenge, Vol. 1, Edited by M. Guillaume, Proceedings of the 22nd Symposium of the International Committee of Aeronautical Fatigue, EMAS Publishing, Sheffield, England, pp. 425-438, 2004.

[41] Jones, K., Clark, P.N. and Hoeppner, D.W., "Pitting Behavior and Residual Fatigue Life of 7075-T6 Aluminum Extruded C-141 Wing", Poster/Paper Presented at the International Committee on Aeronautical Fatigue (ICAF) Lucerne, Switzerland, 2003.

[42] Clark, P.N., Jones, K., Huang, J.T. and Hoeppner, D.W., "Observations from the Inspection of an Aged Fuselage Panel", Journal of Aircraft, Vol. 42, No. 6, pp. 1403-1408, 2005.

[43] Hoeppner, D.W., Restis, J. and Reid, L., "Fatigue Life Enhancement of Structure in the Presence of Corrosion Using Cold Expansion", Proceedings Tri-Service Conference on Corrosion, 2003.

[44] Clark, P.N., Jones, K., Huang, J.T. and Hoeppner, D.W., "Observations from the Inspection and Sectioning of an Aged Fuselage Panel", Aircraft Structural Integrity Program, Conference 2002 Proceedings, Savannah, GA, USA, 2002.

[45] Jones, K. and Hoeppner, D.W., "Effect of Microstructure on Pit-to-Crack Transition of 7075-T6 Aluminum Alloy", Journal of ASTM International, Vol. 3, No. 7, 2006.

[46] Ma, Li and Hoeppner, D.W., "A Finite Element Model for Determining Stress Intensity Factors at Pits Formed by Pitting Corrosion Fatigue", Presented at the 12th. U.S. National Congress of Applied Mechanics, University of Washington-Seattle, Published in Conference Proceedings, p. 182, June 1994.

[47] Bucci, R.J., Konish, H.J., Kulak, M. and Hoeppner, D.W., "A Protocol to Evaluate Consequences of Corrosion Damage in Aging Aircraft", Presented at the FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance, Hampton, VA, USA, 4-6 May 1994.

[48] Ma, Li and Hoeppner, D.W., "The Effects of Pitting on Fatigue Crack Nucleation in 7075-T6 Aluminum Alloy", Presented at the FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance, Hampton, VA, May 4-6, NASA Conference Publication 3274 Part 1, September, pp. 425-440, 1994.

[49] Grimes, L., "Corrosion Pitting Fatigue", M.S. Thesis, University of Utah (Ms. Grimes did the pioneering work on use of the confocal microscope to characterize the shape and depth of pits), 1995.