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Observations from the Inspection of an Aged Fuselage Panel

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An aged aluminum 7075-T6 fuselage panel was inspected for evidence of time-based degradation. Although corrosion pitting and intergranular attack (IGA) were the focus of the investigation, evidence of cracking and fretting wear were documented as well. The investigation was performed at several levels of magnification through the use of magnifying glasses and stereoscopic, metallurgical, and scanning electron microscopy. Comparisons were made for the various levels of investigation. Significant levels of corrosion or cracking damage were discovered in approximately 40% of the fastener holes during the initial low-magnification inspection. Several fastener holes were investigated via sectioning. These specimens were examined with metallurgical and scanning electron microscopes. This investigation revealed tunneling pits, pitting in the countersink region, IGA, cracking and pitting in and away from fastener holes, as well as fretting within the fastener holes and on the faying surface of the panel. This work is significant and applicable to the structural integrity of aging aircraft; it lends credence to the multitude of past and present efforts that focused on time-based degradation of aging aircraft. Teardown inspections emphasize the need for continued research and careful management of aging aircraft fleets.

Nomenclature

β = Weibull slope or shape parameter
η = Weibull characteristic depth
σ = applied (far-field) stress, ksi (MPa)

I. Introduction

ONE current challenge facing the U.S. Air Force is the optimization of the usefulness of each aircraft within the fleet; replacing aircraft is often not economically feasible. The task of maintaining and ensuring aircraft availability and keeping structural integrity within acceptable risk limits becomes the primary objective. Teardown inspection of aircraft is a vital component of the structural integrity process; these inspections provide a sampling of degradation that is the result of actual aircraft usage. In turn, this aids in the structural integrity engineering process through an increased level of awareness and system understanding. The information gained through the teardown process provides aircraft structural integrity program engineers with some of the information needed to assess the viability of methods such as corrosion prevention compounds, fatigue life enhancement techniques, damage tolerance analysis, and inspection programs.

Since 1958, concern for aircraft structural integrity has prompted research, development, and analysis in many arenas.[1] These include, but are not limited to, fatigue, damage tolerance, corrosion prevention, and prediction. On 28 April 1988, Aloha Airlines Flight 243 suffered a catastrophic fuselage failure resulting in an emergency landing and one death. Corrosion in and near fastener holes within the lap joints, in conjunction with concentrated stresses, led to fatigue crack nucleation and multiple site damage (MSD). This damage led to link-up of fatigue cracks and pressurized removal of 18 ft of the upper fuselage crown while cruising at 24,000 ft (Ref. 2). This incident reinforced interest in corrosion, fatigue, and their synergistic behavior. Although Aloha Flight 243 is one of the more commonly known incidents, it is not a singular event. According to a study by Hoeppner et al.,[3] at least 81 passengers and crew of 687 general aviation, commercial, and military aircraft died in accidents and incidents related to corrosion in the United States from 1975 to 1993.

Pitting, exfoliation, and intergranular attack (IGA) are forms of corrosion that frequently occur in high-strength aluminum alloys commonly used on aircraft. These forms of corrosion are often discovered side-by-side in susceptible components; IGA is usually a precursor to pitting and is commonly found in conjunction with pitting in aluminum alloys.[4,5] According to an Australian study,[6] pitting and exfoliation can be considered to occur concurrently; from the perspective of fatigue, these corrosion mechanisms can be detrimental to structural integrity.

A study presented at the International Committee on Aeronautical Fatigue in 1999 (Ref. 7) contended that corrosion (in that case, only percent area loss or thickness loss was addressed) on the order of 10% area loss, coupled with MSD, raised the probability of fracture (POF) to the threshold level of 1×10^{-5} per flight hour (FH), whereas corrosion more severe than 10% cross-sectional area loss, coupled with MSD, raised the POF/FH to $>1 \times 10^{-5}$. The study points out that nondestructive inspections (NDIs) can detect area loss as low as 5% with good reliability. However, the analysis did not specifically consider pitting and IGA, both of which are less likely to be reliably detected via NDI at levels of damage that have been shown to transition to fatigue cracking in laboratory studies ($<$5–250 μm).[4,8] Significant corrosion was discovered on

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several locations throughout the subject panel of this investigation; therefore, it is likely that the pitting and IGA discovered in this study will increase the POF/FH for this and similarly managed aircraft.

A significant amount of research has been performed in the area of pit-to-crack transition under fatigue conditions, with all concluding that corrosion pits act as fatigue crack origins.[9–13] Along with this research, modeling of pits within the fatigue domain has been accomplished.[14,15] Fretting, commonly associated with aircraft fasteners, has also been found to substantially reduce fatigue life.[16–28]

This study details the inspection of a naturally corroded or aged fuselage panel removed from service. The inspection focused on the documentation of pitting and IGA.

II. Approach and Results

The fuselage panel was delivered to the University of Utah from Lockheed Martin Aeronautics Co., Marietta, Georgia, in February 2002. The history of the panel could not be traced by the investigation team; the panel was known to have been in service for a significant period, then removed and stored prior to shipping for a relatively short interval. Upon receipt of the panel, the front and back surfaces were documented via digital photography. The panel as received is shown in Fig. 1. Hand-held magnifying glasses, with magnification factors of 4× and 7×, were used to inspect the surfaces of the panel. In short order, it became clear that the vast majority of the visible time-based degradation was concentrated in and near the fastener holes. To execute timely investigation, efforts were focused on the fastener holes. Each fastener hole and its surrounding surface was inspected for cracking and corrosion. Pitting and exfoliation corrosion were the focal points of the investigation; however, other types of corrosion and degradation or damage were also noted.

Each fastener hole was marked during these inspections to indicate its perceived damage state. Each hole was designated using N (no visual indication of corrosion, cracking, or other degradation), NIS (not inspected due to damage in or around the hole, usually mechanical damage or the presence of substantial paint or sealant in the hole), C (indication of corrosion found), P (pitting found, possibly from various causes), or X (cracking found).

Significant levels of degradation were discovered and documented throughout the panel. Frequently, several forms of degradation were found in the same fastener hole. For example, a single fastener hole may have shown indications of pitting, other corrosion, cracking, and other degradation (usually fretting). For tabular purposes multiple designations were consolidated according to the following rules:

1) If any pitting is present or suspected to be present, P dominates.
2) For X and C, cracking dominates.
3) Other degradation was always found along with pitting, other corrosion, or cracking and therefore did not require a separate designation.

Single designations retained their original classifications. These rules were assigned by the inspection team with pitting deemed as the damage state of primary exploration. After the initial inspection with hand-held magnifying glasses was completed, the panel was sheared into 31 sections of approximately equal size. From these sections, the holes and their initial damage designations were counted and recorded. The results from this preliminary analysis are shown in Fig. 2.

Figure 2 illustrates the discovery from the macroscopic inspections that were performed with 4× and 7× power handheld magnification glasses. Note that nearly half (47%) of the fastener holes were initially designated as having no indication of damage (N). This was later proven to be incorrect, although the aid of magnification showed more damage than the unassisted eye.

In the next step, further inspection of the holes was performed using a stereoscope. A total of 2606 holes were present on the panel. Because of this high number, each panel section had a few holes selected for careful inspection using the stereoscope. During the initial magnifying glass (macroscopic) inspection, each hole was labeled with a designation. Over 1600 holes were either not inspected due to damage or did not have any visible damage at the 4–7× magnification level. The holes to be inspected using the stereoscope were identified from the remaining 980 holes classified as having some form of damage, along with 8 holes with no indication of damage. The "no indication of damage" holes were selected to identify whether or not smaller levels of damage existed than were detectable via the 4–7× magnification level. The following outlines the selection criteria for inspection with the stereoscope (10–70×): 1) every hole with a possible crack, 2) every other hole with possible

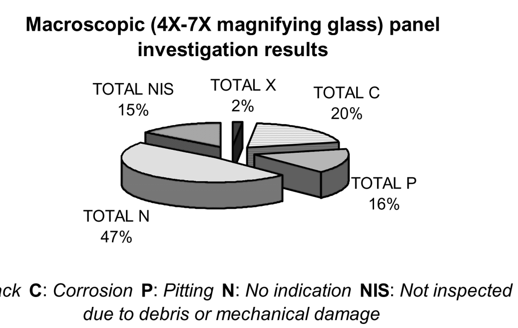

Fig. 2 Results of initial macroscopic investigation.

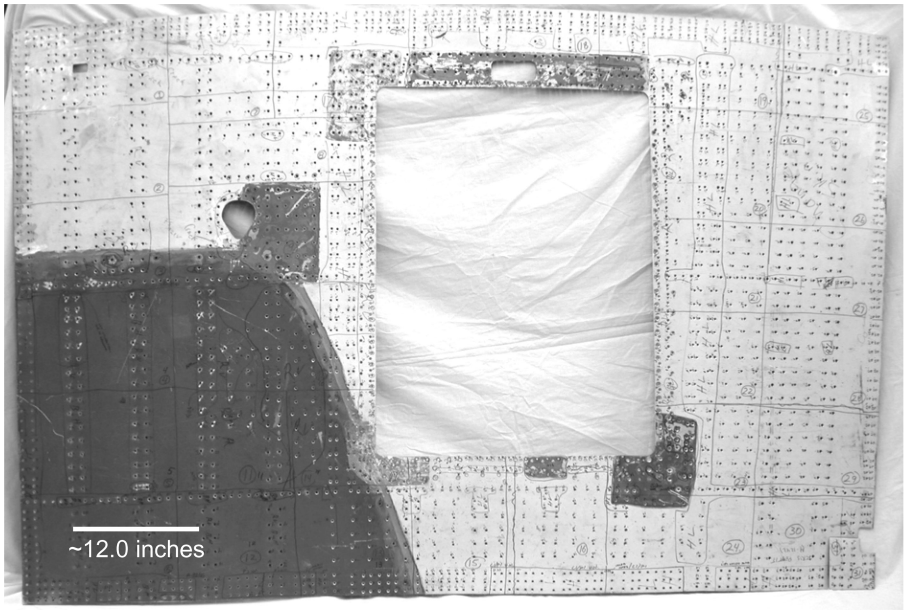

Fig. 1 The inspected panel.

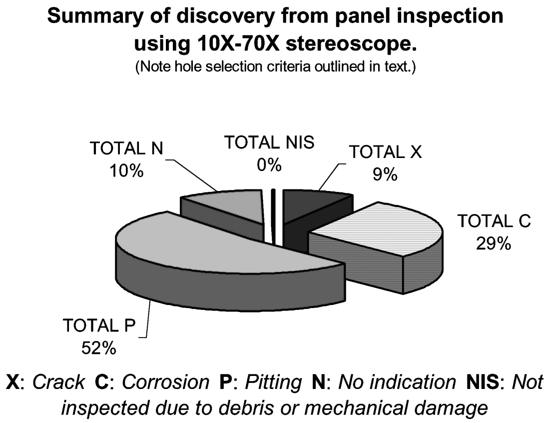

Fig. 3 Results of stereoscopic inspection.

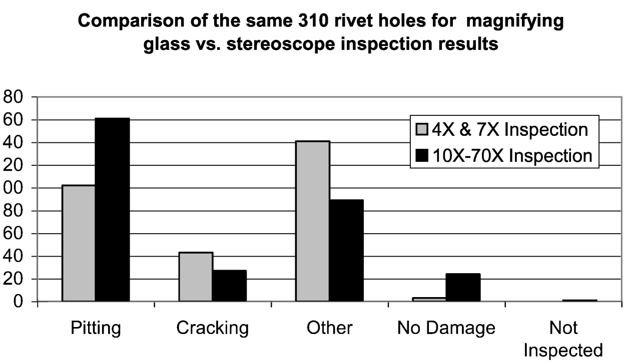

Fig. 4 Macroscopic vs stereoscopic comparison.

pitting, 3) every fifth hole with other corrosion or other degradation, and 4) eight holes selected with no indication of damage.

Each panel section was cleaned in acetone for approximately 12–16 h before the stereoscopic inspection was performed. After cleaning, the holes to be investigated were labeled. The stereoscopic investigations took place at 70× magnification. New designations were assigned to the holes based on discovery; areas identified as candidates for metallurgical sectioning or scanning electron microscope (SEM) inspection specimens were noted.

Figure 3 shows the results from the stereoscopic inspections. Figure 4 compares the difference in discovery between the macroscopic (4–7× magnification) and stereoscopic inspections. An interesting item to note in Figs. 3 and 4 is that the number of fastener holes with no indication of damage (N) increased. This indicates that some of the fastener holes that were suspected of having some level of damage were incorrectly diagnosed; this was primarily due to residual grime and sealant that were not removed prior to macroscopic inspection but were removed during the cleaning process prior to the stereoscopic inspection.

Figure 5 shows results from the SEM and metallurgical microscope (metscope) investigation. The trend of increased numbers for N was reversed upon microscopic inspection. This is displayed in Fig. 5; 12 fastener holes were suspected to have no damage, whereas only 5 were found to display no damage upon SEM and metscope investigation. The numbers increased in nearly all categories except N; for the microscopic investigation, these observations can be clarified by the following statements:

1) The more intently one investigates, the more one is likely to see and/or find.

2) If multiple types of damage were documented in a given hole, each type of damage was recorded for that fastener hole. (For example, a hole was determined to have pitting, IGA, and cracking; that hole contributed to three types of damage documented.)

Specimens were identified for cross-sectional analysis due to the presence of corrosion damage or cracking (typically intergranular). Once a fastener hole was selected for this type of analysis, it was sheared from the panel and then cut to the appropriate geometry using a diamond-tipped metallurgical saw. The specimen was mounted into a metallurgical disk composed of Bakelite using a thermal mounting press. After mounting, the specimen was polished according to the following procedure.

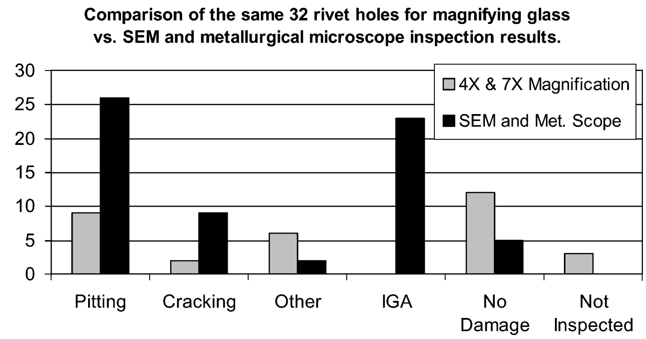

Fig. 5 Macroscopic vs microscopic comparison.

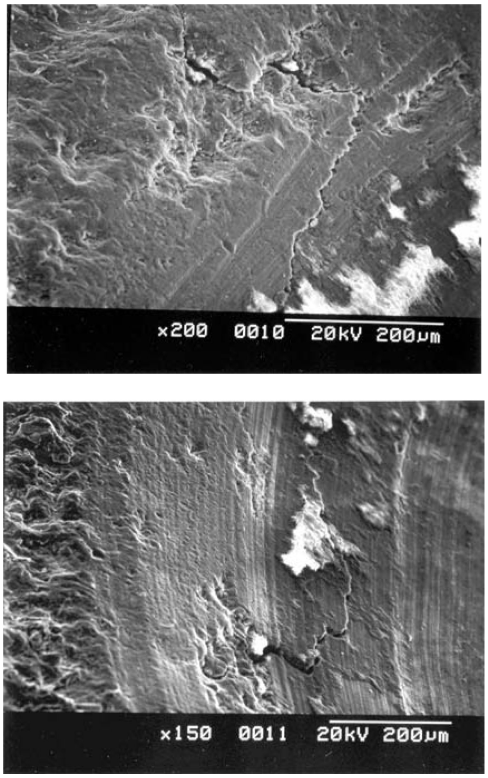

Fig. 6 Examples of pitting with cracking in fastener holes.

Each specimen was hand polished using a Buehler Handimet with the following grit sizes, in order: 1) 240, 2) 320, 3) 400, and 4) 600 grit. The second phase used alpha alumina slurry to polish the specimens with the Buehler Ecomet IV and the following grit sizes, in order: 1) 6.0, 2) 1.0 μm. The final step was performed manually using 0.3-μm alpha alumina slurry.

Visual inspection was performed on each specimen to ensure polishing was complete. Each specimen was cleaned in acetone for 15 min after the final polishing step. After cleaning, the specimens were stored in a desiccation chamber until needed.

The cross-sectional specimens were examined first using a metallurgical microscope. The damage state was characterized and if further investigation was warranted, the specimen could be further examined using the SEM or could be polished again, removing material to gain additional information. The same polishing procedure was used to remove the desired amount of material, and investigations continued until the necessary information was obtained.

Figure 6 reveals discovered examples of pitting and cracking on the surface of countersunk fastener holes. (Note tool marks on the faying surface of the countersinks.)

IGA and pitting are highlighted in the metallurgical microscope images depicted in Fig. 7. Note the tunneling behavior of the captured pitting as well as the significant penetration of the IGA into the material.

Fields of pitting among the faying surfaces in and around the fastener holes was common; this is typically associated with fretting. The tunneling behavior of the pitting is also noteworthy; this behavior is common in aluminum alloys.[5,8] Tunneling pits hide the true extent of damage from surface investigations.

Surface investigation compared with sectioned investigation revealed dissimilar pitting characteristics. Weibull analyses were performed on pitting depth data from both surface investigation and sectioned investigation. Figure 8 shows the difference in the trends for the two types of investigation. Series 1, represented by the triangles, shows results for the surface investigation; series 2, represented by the upside-down triangles, shows sectioned investigation results. The slope (β) and characteristic depth (η) are listed in Table 1.

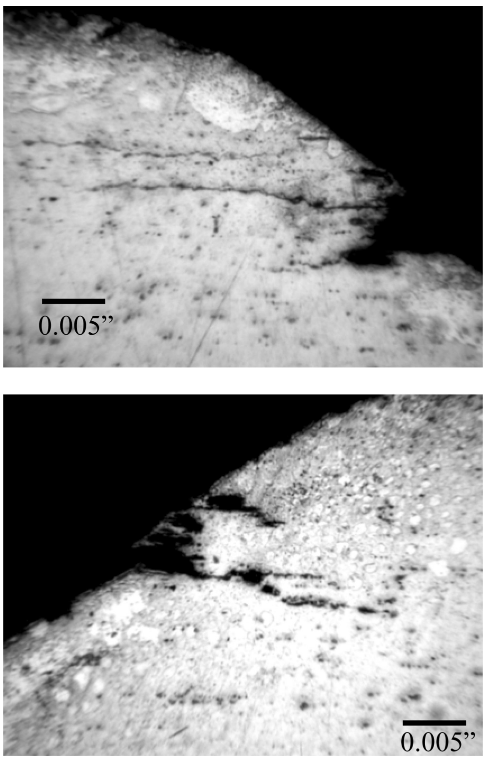

Fig. 7 Examples of pitting with associated IGA (specimen sectioned and polished prior to metallurgical microscope investigation).

The Weibull analysis for this investigation is not meant to be a reliability analysis; it is simply used as a tool to illustrate the characteristics of the pitting behavior and the difference between the two investigation techniques. The slope or β for both investigation techniques is greater than one, an indication of increasing occurrence; however, β for the section investigation is approaching one ($\beta = 1$), which suggests the data are close to an exponential fit. From this analysis, the more important feature is the characteristic depth comparison; the characteristic depth (η) for the surface investigation is approximately 29 μm, whereas η for the sectioned investigation is approximately 71 μm. The significance of this comparison is that it statistically shows the difference between the two investigation techniques. Surface inspections do not reveal many hidden details of corrosion damage whereas sectioning shows significant details of corrosion damage that may be hidden from surface inspections.

The widespread amount of pitting documented in this investigation is important to note. Detrimental effects of corrosion (particularly pitting) on fatigue have been well documented; this study underscores the propensity for pitting and IGA occurrence within an aircraft aluminum environment.

III. Discussion

Figure 2 shows the results from a hand-held magnifying glass investigation. This inspection revealed pitting in 16% of the inspected holes, cracking in approximately 2%, and other corrosion or wear damage (e.g., fretting) in 20%. Totaled, some form of time-related degradation (aging effects) was discovered in approximately 38% of the fastener holes. This is a significant number because each of these degradation forms has been proven to lead to early nucleation of fatigue cracking as well as significant MSD.

The significance of higher magnification inspection is evident in the comparison of the records in Figs. 3–5; the closer one inspects, the more one is able to find. This may seem irrelevant; however, in

Table 1 Weibull analyses slope and characteristic depth for surface and sectioned investigations

Investigation type	Slope (β)	Characteristic depth (η), μm
Surface	1.9	28.76
Sectioned	1.2	70.83

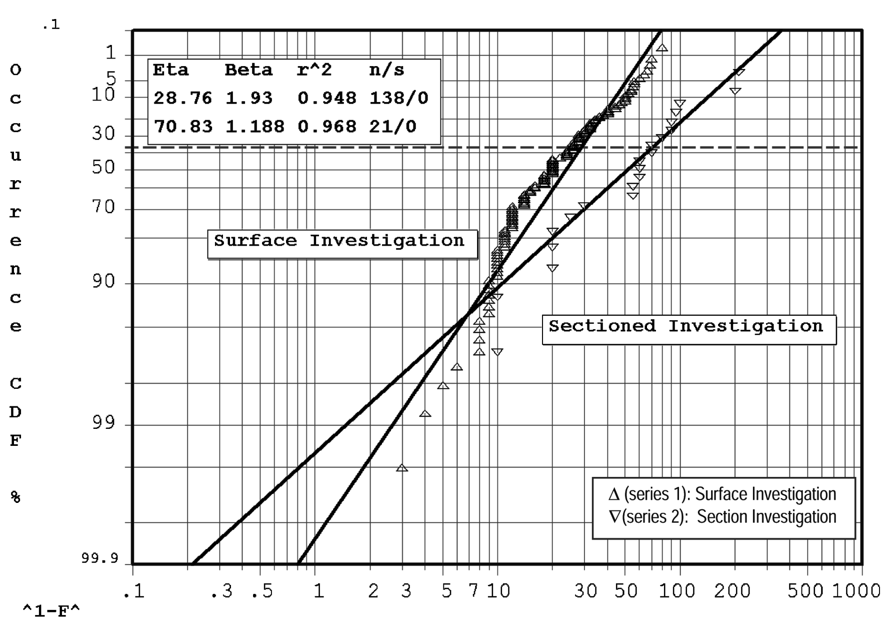

Fig. 8 Weibull plot of pit depths for surface investigation vs section investigation.

many cases, pitting magnitudes less than 0.004 in. (often as small as 0.0005 in. in depth)[5,8] have been documented to nucleate fatigue cracks at relatively low stress levels. In the case of seemingly minor pitting depths, the corrosion damage was not discovered until SEM investigation at magnifications of greater than 100×. Figures 3 and 4 compare the discovery of damage between a magnifying glass and a stereoscope. The stereoscope allows for high magnifications but also provides a three-dimensional feature that proved beneficial when inspecting for characteristics such as pitting. Note that the same 310 fastener holes were inspected for comparison in Figs. 3 and 4.

Figure 5 compares the results of the sectioning investigation via metallurgical microscopic inspection with the high-magnification inspection using an SEM. One of the main differences of Fig. 5 from the other figures is the classification of damage. For each of the other figures, each fastener hole was only assigned one type of damage (in line with the stated classifications). For the data in Fig. 5, if a fastener hole showed more than one type of damage, then all forms of damage were counted. Only 32 fastener holes were inspected, yet there are 65 damage classification counts recorded in Fig. 5. Note the change in the "no damage" classification: 12 fastener holes were inspected that showed no signs of damage at 4–7× magnification; however, after SEM investigation, only 5 of those 12 holes still qualified to be placed in the "no damage" category. Pitting was found in 26 of the 32 fastener holes along with some level of IGA. Cracking was documented in 9 of the 32 fastener holes. The "other" classification began with six fastener holes that were suspected to have some type of corrosion or wear damage and all but two were reclassified into an appropriate category. The two remaining "other" fastener holes were eventually classified as having mechanical damage (likely from fastener removal).

Several of the sectioned specimens revealed tunneling/undercutting of pits on both top and bottom of the panel. This tunneling behavior has been documented in pitting growth studies on pristine aluminum alloys.[5,8]

For lower magnification levels (stereoscope, 10–70×; magnifying glasses, 4–7×), IGA below the 0.004 in. level was not detectable. Larger scale IGA (>0.004 in.) was detectable and was usually, but not always, associated with pitting. It must be stated that the inability to always associate larger scale IGA with pitting was likely due to reduced resolution because of the lower magnification levels. All pitting documented with SEM inspection was associated with IGA. Also utilizing the SEM, all intergranular attack that was discovered could be associated with pitting. Much of the intergranular attack was associated with exfoliation as documented in Figs. 6 and 7.

The variation in the results from the different investigation techniques and associated pitting depth measurements are demonstrated in Fig. 8. Beyond the divergence between the pit depths and shapes, the section investigation revealed a propensity for IGA and intergranular cracking; one of these cracks measured 2980 μm (nearly 3.0 mm) in length, with several measuring from 600 to 1800 μm. Pitting corrosion linked with intergranular corrosion can readily exceed the commonly perceived "rogue flaw" of 0.05 in. (1.27 mm). Therefore, it is imperative that corrosion receives adequate consideration during design, analysis, and aging fleet sustainment. With regard to aging aircraft, this research demonstrates that 0.05 in. is not a rogue flaw. The effect of intergranular corrosion on structural integrity is not well understood; coupled with pitting and MSD, the effect becomes even more anomalous. It will become increasingly important to reevaluate the current approach to analysis of aging aircraft as structures are utilized and continue to degrade.

A significant degree of corrosion damage was discovered and documented on this fuselage panel. This investigation has revealed the inability of corrosion protection compounds to completely prevent corrosion degradation. The preponderance of corrosion damage evidence coupled with the tendency for fatigue cracks to originate from these types of damage mechanisms will increase the risk of incident associated with continued operation of aging aircraft. The risk increases when MSD is considered.

Corrosion, particularly pitting, is somewhat mysterious when used to predict pit-to-crack transition; this is a branch of science still in its infancy with significant research and analysis yet to be performed. The need for continued efforts to understand corrosion and corrosion fatigue behavior and their effects on structural integrity is evident and will play a crucial role in future endeavors to maintain fleets of aging aircraft. These are significant challenges for the aircraft structural integrity community to address.

IV. Summary of Findings

An aged 7075-T6 aluminum fuselage panel was inspected for corrosion at several levels of magnification, through the use of magnifying glasses as well as stereoscopic, metallurgical, and scanning electron microscopy. The findings are as follows:

1) Pitting, IGA, cracking, and/or other time-dependent degradation were discovered in more than 38% of the inspected fastener holes. Corrosion was found in the bores of holes and countersink regions, as well as on faying surfaces away from fastener holes.

2) More focused investigation at higher magnification levels provided further detailed results that corrected erroneously categorized fastener holes, revealing no damage in several holes that were assumed to be damaged to some degree, as well as documenting pitting, IGA, and cracking in holes that were previously designated as having no indication of damage.

3) Utilizing SEM inspection techniques, in all cases within this study, pitting was found to be associated with IGA.

4) Also found during SEM inspection, IGA was documented without the presence of pitting. However, this was the case in less than 4% of the fastener holes within this study.

5) Surface investigation does not reveal adequate information with regard to pitting or intergranular corrosion.

V. Conclusions

The results of the 7075-T6 aluminum alloy aged fuselage panel investigation indicate that a significant amount of corrosion, multiple source pitting, and cracking existed in about 38% of the fastener holes on the panel. It is judged that this damage was present on the source aircraft during service. The tendency for pits to transition to cracks is well documented, even at pit depths of less than 10 μm (Refs. 2, 4–6, 8–12, 14, and 15). The number of locations and levels of pitting observed on the panel create the potential for MSD, potentially leading to accelerated crack growth due to pairs of adjacent cracks growing toward each other, as well as crack linkage, which may cause failure by net section yielding. It is judged that this failure scenario is likely due to the prevalence of time-related degradation documented throughout this investigation. Corrosion and pitting can have significant effects on an aircraft's structural integrity, increasing the importance of damage tolerance analysis and the need for further teardown investigation and experimentation of aged aircraft panels for improved understanding of evolving discontinuity states.

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