EVALUATION AND QUANTIFICATION OF FRETTING DAMAGE AND CORROSION PIT MORPHOLOGY USING THE CONFOCAL MICROSCOPE

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Fretting fatigue and corrosion pitting experiments were conducted on 7075-T6 and 2024-T3 aluminum alloy specimens. The results from these studies are presented in the paper. From the confocal microscopy analysis of fretting damage, it was observed that the fracture of 7075-T6 aluminum alloy specimens occurred because of fretting-nucleated cracks on the faying surface. However, for 2024-T3 specimens, the confocal microscopy analysis of fretting damage suggested that fretting-nucleated multiple-pits are responsible for the final fracture of the specimen. Moreover, the quantified fretting-nucleated pits revealed a correlation between the area of the pit and the pit depth and pit dimension perpendicular to the applied load. From this study, it was observed that the cause of final instability under fretting fatigue conditions was material specific.

Confocal microscopy was also used to observe changes in corrosion pit morphology with changes in loading scenario. Experiments were conducted on 7075-T6 aluminum alloy specimens in 3.5% salt water for 24 hours under zero, sustained, and cyclic loading conditions. Confocal microscopy analysis of the pits after loading revealed that fatigue-nucleated pits were approximately three times larger in cross sectional area than those grown under zero and sustained load conditions. Pits on the sustained and zero loaded specimens were found to be of approximately the same size in cross-sectional area. From this study, it was concluded that mechanical loading environment has an effect on corrosion pit morphologies.

The power of using confocal microscopy to characterize fretting and corrosion pitting has clearly been demonstrated in these two investigations.

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INTRODUCTION

It is well documented that fretting and corrosion are significant safety issues in aircraft structural components [1]. Fretting and corrosion often act synergistically with fatigue and other mechanisms leading to a component failure. Risk mitigation requires an in-depth understanding of each degradation mechanism and its synergism with other failure modes. Although there are many failure mechanisms worthy of further study, fretting and pitting corrosion are the focuses of this research. In this research, the confocal microscope was used to characterize fretting damage and corrosion pit morphology to provide additional insight into these failure mechanisms. The confocal microscope is an important tool in biological research for imaging. It has been used successfully here to develop a better understanding of fretting and corrosion pitting damage. The first part of this work examines results from a study to evaluate and quantify fretting induced fatigue damage using the confocal microscope on two aluminum alloys viz. 7075-T6 and 2024-T3. Additionally, the confocal microscope has been used to examine results from a study to characterize the effect of mechanical stresses on corrosion pit morphology on 7075-T6 aluminum alloy specimens. In both studies, the versatility and high resolution imaging capabilities of confocal microscopy were exploited as briefly explained below.

WHY CONFOCAL MICROSCOPY?

The popularity of confocal microscopy arises from its ability to produce blur-free, crisp images of thick specimens at various depths. In contrast to a conventional microscope, a confocal microscope projects only light coming from the focal plane of the lens. Light coming from out of focus areas is suppressed. Thus, information can be collected from very defined optical sections perpendicular to the axis of the microscope. Confocal imaging can only be performed with point wise illumination and detection, which is the most important advantage of using confocal laser scanning microscopy [2]. An additional feature of the confocal microscope is that it can optically section thick specimens in depth, generating stacks of images from successive focal planes. Subsequently the stack of images can be used to reconstruct a three-dimensional view of the specimen. Once acceptable images have been developed, the confocal microscope is able to provide a digitized image to a computer screen. These digitized images are then analyzed using a pixel counting software package, NIH Image (created by the National Institute of Health), that allows area measurements. In the case of the three-dimensional stacked images, NIH image is able to make volumetric measurements as well. Currently, biologists have had success in obtaining volumetric measurements in opaque media, but in order to utilize this capability for metallic materials, further research is necessary.

EVALUATION AND QUANTIFICATION OF FRETTING
INDUCED FATIGUE DAMAGE

Fretting fatigue is described as the progressive damage to a solid surface that arises from fretting [3]. Fretting is defined as a wear phenomenon occurring between two surfaces having oscillatory relative motion of small amplitude [3]. Fretting may produce
several forms of damage on the faying surface including pits, oxide debris, scratches, fretting and/or wear tracks, material transfer, surface plasticity, fretting craters, and cracks at various angles to the surface [4]. The intensity and the nature of fretting damage varies depending upon the applied maximum fatigue stress and the resulting damage morphology. It would be beneficial to quantify fretting damage morphology to establish a better understanding of the three-dimensional nature of fretting damage. The primary objective of this study was to quantitatively characterize fretting damage that resulted on the fatigue specimens. Fretting fatigue experiments were performed in laboratory air at various maximum fatigue stress levels at a constant normal pressure and the resulting fretting damage was quantitatively characterized as explained below.

EXPERIMENTAL DETAILS TO CHARACTERIZE FRETTING INDUCED FATIGUE DAMAGE

Fretting fatigue tests were performed using a closed loop, electro-hydraulic, servo-controlled testing system. As the fatigue specimen deforms during the application of the fatigue cycle, a relative movement occurs between the fatigue specimen and the fretting pad. This motion, acting under various magnitudes of applied normal and fatigue loads, results in fretting. Fretting fatigue tests were performed on flat fatigue specimens in contact with fretting pads. A supporting block was placed beneath the fatigue specimen test section to prevent bending of the specimen due to application of the normal load. An axial fatigue load was applied horizontally to the fatigue specimen. A normal pressure was applied vertically through the fretting pad that was in contact with the fatigue specimen. Fretting fatigue experiments were conducted on two aluminum alloy fatigue specimens viz. 7075-T6 and 2024-T3. The fretting pads were made of these materials respectively. The configurations of the fatigue specimen and the fretting pad are shown in Figure 1. The maximum fatigue stress ($\sigma_{\text{max}}$) level was varied from specimen to specimen at a constant normal stress ($\sigma_n = 13.8 \text{ MPa or 2 ksi}$). The static normal load was calculated by multiplying the contact pad area with the normal stress. All tests were conducted in laboratory air (room temperature) at $R = 0.1$ and frequency of 10 Hz. During testing, fretting fatigue experiments were interrupted at a predetermined number of cycles to analyze the damage using the confocal microscope. Table 1 shows the fretting fatigue test results.

CHARACTERIZATION OF FRETTING INDUCED FATIGUE DAMAGE USING THE CONFOCAL MICROSCOPE

The confocal microscopy analysis of the specimen faying surface revealed at least three stages in the nucleation and development of fretting damage leading to the final fracture of the specimens. The first stage was the appearance of a black colored (for aluminum alloys) debris like a "smudge" on the faying surface of the specimen in the early period of fretting fatigue life. After a certain number of fretting fatigue cycles, this was followed by a removal of material as seen in the digitized images produced by the confocal microscope. The third stage of the development of the damage was material dependent. For 7075-T6, subsequent fretting fatigue cycles generated multiple cracks on the faying surface, whereas in 2024-T3 it resulted in the generation of fretting nucleated
multiple pits on the faying surface as illustrated in the thumbnail images in Figures 2 (a) and 2 (b).

The most important observation from the confocal analysis of the fretting damaged specimens was that fretting generated multiple cracks on the faying surfaces of 7075-T6 aluminum alloy specimens. The nucleated cracks (at the edge of the contact pad) are believed to be responsible for the reduction of the residual strength of the specimens leading to the final fracture. On the faying surface of the 2024-T3 specimens there were no cracks found; however, multiple pits were observed on the faying surface (also at the edge of the contact pad where fracture occurred) that may have caused the fracture of this specimen. This observation suggests that the cause of final instability under fretting fatigue conditions is material specific.

Moreover, using NIH Image, the lengths of fretting induced cracks on the faying surface of the fatigue specimen were measured. In addition, fretting damage was quantified in terms of material removal by characterizing the depth as well as the geometry of fretting-generated pits on the faying surface of the specimen. Pit size in terms of pit depth ($P_d$), pit area ($P_A$), pit dimension perpendicular ($P_{Dy}$), and parallel ($P_{Dx}$) to the applied load were also quantified. Figure 3 shows a schematic representation of the pit geometry that was characterized in this study.

The crack lengths measured on the faying surface of 7075-T6 specimens were found to be in the range from 20 $\mu$m to 169 $\mu$m. It was observed that the quantified fretting nucleated cracks were the smallest at 241 MPa (35 ksi) when compared to the two lower stress levels tested in this study as illustrated in the thumbnail images shown in Figure 4.

It is possible that longer cracks on the faying surface of 7075-T6 specimens subjected to lower maximum fatigue stress levels result from longer fretting fatigue life (more time for the crack[s] to grow) when compared to those at higher stress level. However, the material removal (in terms of depth) was greater at 241 MPa (35 ksi) maximum fatigue stress level when compared to 172 MPa (25 ksi) or 138 MPa (20 ksi). It was observed that at 241 MPa (35 ksi) the depth of material removal was on the order 5 to 18 $\mu$m. At 172 MPa (25 ksi) it was between 3 and 10 $\mu$m. At 138 MPa (20 ksi) the material removal was found to be insignificant. Figure 5 shows confocal images illustrating removal of material by fretting on the faying surface of 7075-T6 specimen at 241 MPa (35 ksi) maximum fatigue stress level. Figure 5(a) shows a confocal image where the maximum material removal in terms of depth was observed. The depth of material removal at this point was quantified to be 18 $\mu$m. As well, Figure 5(b) shows material removal on the same specimen (at different location) that was found in the range 5 - 9 $\mu$m. Figures 6 and 7 show graphs of crack size vs. maximum stress and material removal vs. maximum stress respectively.

As mentioned before, one of the effects of fretting is that it may produce pits. When a 2024-T3 alminum alloy specimen was tested under fretting fatigue conditions with maximum fatigue stress of 207 MPa (30 ksi) at a normal stress of 13.8 MPa (2 ksi), it fractured in 81,100 cycles. Subsequently, the confocal analysis revealed multiple pits along the edge of the faying surface of the fatigue specimen where the fracture occurred. As shown in Figure 8, these pits varied significantly in morphology. Using the confocal microscope, the depths of these pits were quantified by scanning along the Z axis. The depths of the pits ($P_d$) varied from 8 to 26 $\mu$m. In addition, the pit dimension
perpendicular to the applied load \((P_{Dy})\) was found in the range from 10 to 36.82 µm. The pit dimension parallel to the applied load \((P_{Dy})\) was found in the range from 8 to 42.07 µm. The area of the pit \((P_A)\) was quantified and was in a range from 26 to 1478 sq. µm. Figure 8 shows a confocal image revealing fretting nucleated multiple pits on the faying surface of the 2024-T3 aluminum fatigue specimen.

Additionally, the quantified pit parameters also revealed a relationship between applied load and morphology. For example, the pit depth \((P_d)\) has correlated with the pit dimension perpendicular to the applied load \((P_{Dy})\) as well as with the pit area \((P_A)\). Also, the deeper the pit depth, the greater the area of the pit and the larger the pit dimension. Figures 9 and 10 show graphs illustrating the correlation between pit depth vs. pit area and pit dimension perpendicular to the applied load respectively.

It has been proposed by some researchers [5] that the fretting damage mechanism can be described as two independent processes. One process results in material loss from the faying surfaces and is related to fretting wear mechanism and the other process produces cracks that are related to the fretting fatigue mechanism. However, this study has revealed that the fretting damage process comprises both material removal and nucleation of cracks on the faying surface of the specimens under fretting fatigue conditions.

To conclude the discussion, it appears that the fracture of 7075-T6 aluminum alloy specimens may have resulted from a high stress concentration developed from fretting induced cracks on the surface. However, fretting-nucleated multiple pits on the 2024-T3 specimen, which also led to high stress concentrations, would also have led to the eventual failure of this specimen.

In general, 2024-T3 will form pits in a corrosive environment more readily than 7075-T6 because of the Cu phases. The constituent particles are CuAl compounds that are very reactive with the matrix as well as the environment. Thus, 2024-T3 is very susceptible to pitting but resistant to SCC and exfoliation. In addition to the atmospheric reaction, fretting motion induces faster material removal (as a result of faster oxide removal in discrete areas) resulting in the nucleation of pits on the surface. These observations suggest that even though 2000 series aluminum alloys could tolerate larger critical crack size (higher fracture toughness) but they may be susceptible to fretting induced pitting.

Experiments also were conducted on 7075-T6 aluminum alloy specimens in 3.5% salt water for 24 hours under zero, sustained, and cyclic loading conditions as discussed in the next section.

**EVALUATION AND QUANTIFICATION OF CORROSION PIT MORPHOLOGY**

In 1916, it was known that high purity iron would locally corrode. Although corrosion mechanisms were not well understood, it was postulated that a mechanical strain could have an affect on pitting in iron. Aston suggested that a mechanical environment would create areas of potential difference resulting in rapid corrosion in the more highly strained areas [6]. These ideas were tested later, when much more was known about corrosion mechanisms in general, by deWexler and Galvele, Cox, and Li Ma [7-9]. DeWexler and Galvele studied pitting in aluminum specimens in various electrolytes under strain. They found that the pitting potential was not changed by the
strain; however, specimens exhibited smaller pits in increased numbers when compared to specimens not strained [7]. Cox found that under different maximum alternating stresses, aspect ratio (depth/diameter) increased in pits grown in 3.5% NaCl [8]. For pits growing under different alternating load frequencies, Li found that this had no effect on pit morphology [9].

Research activities in the area of corrosion pit morphology have been motivated primarily by the need to develop finite element models to predict pitting corrosion fatigue life. A hemispherical shape assumption was usually made [9,10]. A more complete understanding is required of corrosion pit morphology if more realistic models are to be created. In the present study, it was hypothesized that under differing load scenarios, pits would develop differing morphologies.

EXPERIMENTAL DETAILS TO CHARACTERIZE CORROSION PIT MORPHOLOGY UNDER ZERO, SUSTAINED, AND FATIGUE LOADING CONDITIONS

Specimens with a dog-bone shape (similar to Figure 1a) were machined from 7075-T6 aluminum alloy blocks and then sliced into 2.54 mm (0.1 inch) thick sheets. The specimens were randomized to eliminate effects of grain structure. Pitting surfaces were prepared by polishing using a succession of SiC papers (240, 320, 400, and 600 grit). In order to prevent pitting on the other surfaces of the specimens, clear silicone was applied to those surfaces. This protection was needed to avoid premature failure of the specimen due to stress corrosion cracking or pitting corrosion fatigue. Clear Plexiglas™ was used to create environmental chambers. The chambers were clamped over the thin sections of the specimens. All specimens were oriented with the pitting side (unprotected side) facing up. A 3.5% weight salt-water solution was prepared and an oxygen saturation condition was created. Flow regulators were used in an attempt to control solution flow; however, leakage was observed at the edges of the environmental chambers. Regardless, continuous flow was established in all cases. Every specimen was exposed to both salt-water and mechanical environment for 24 hours.

Two specimens were tested under each loading condition. Figures 11, 12, and 13 show the setups for each test. The zero load specimens were simply placed on stands in a drip tray as seen in Figure 11. The sustained load setup is shown in Figure 12. Specimens were attached to special grips that allowed the pitting surface to face upward and the specimen to experience a constant 147 N (33-lb.) load. The 147 N load was selected since it was the minimum fatigue load experienced by the specimens in the fatigue test. The fatigue load setup is shown in Figure 13. A closed loop, electro-hydraulic, servo-controlled testing system, horizontal fatigue machine with a MTS 440 controller was used to apply a stress of 82.8 Mpa or 12 ksi to the specimens. A stress ratio (R value) of 0.1 was used at a frequency of 10 Hz.

After exposure to the environments, all specimens were rinsed and ultrasonically cleaned in acetone. They were stored in a desiccation chamber until all testing was completed. The pitted surfaces were then sectioned and placed against a clean, unexposed piece of 7075-T6 aluminum. This mounting technique was used to protect the pitted surfaces from polishing damage. Specimens were then polished. Upon polishing, the specimens were checked using an optical metallograph for pits. If a sufficient pit was
found, the mounting was set aside for examination with the confocal microscope; otherwise, the mounting was polished further until a pit was located.

After pits had been found, the confocal microscope was used to characterize them. The confocal microscope is able to focus on a small optical section by sending the laser beam through an aperture. If the aperture is fully open, then the depth of field is 3.7 microns at 60x. To ensure accurate measurements, a smaller depth of field is preferred since a field of 3.7 microns is obtainable from a good quality light microscope. When the confocal aperture is fully closed; however, the depth of field is 0.7 microns. In order to take advantage of the smaller depth of focus, it is necessary to create a surface that is flat and parallel to within at least 0.7 microns. This was possible only through the symmetric placement of specimens in an automatic polishing disk.

CHARACTERIZATION OF CORROSION PIT MORPHOLOGY UNDER ZERO, SUSTAINED, AND FATIGUE LOADING CONDITIONS

Surface examination of the zero-load and sustained-load specimens revealed very small, dispersed pits. When sectioned, the sustained-load specimens contained pits of approximately the same size as the zero-loaded specimens (compare Figures 14 and 19). In contrast, surface examination of the fatigue loaded specimens exhibited general corrosion covering the entire surface of the specimens and large pits were seen when the fatigue specimens were sectioned. It was suspected, based on the results of the metallograph pictures, that the pits that formed on the fatigue-loaded specimens had grown along the grain boundaries. To confirm this, specimens were polished and etched to discern the boundaries. As is visible in figure 20, pits did nucleate and grow along grain boundaries. It was subsequently found that pits on specimens exposed to zero and sustained loads were too small to reveal any association with grain structure. After completing examination with the metallograph, digitized images were obtained from the confocal microscope. Figures 14 through 19 are some of the digitized images of the pits examined using the confocal microscope. More than 60 pits were examined, often several pits on each specimen. Upon obtaining images from the pits, NIH Image was used to quantify the pit sizes. Although the fatigue specimens had considerably larger pits, there was large variation in pit size on the same specimen. Based on the area measurements from the NIH Image software, pit size ranged from 398.04 $\mu m^2$ to 10763.88 $\mu m^2$ on the fatigue-loaded specimens. Table 2 provides a truncated summary of these results showing the largest and smallest pits found in each load type. As is seen in the table, the smallest pit found on the fatigue specimens was three times larger than the largest pit found on the zero and sustained load specimens.

CONCLUSIONS

Based on the analysis of fretting induced fatigue damage on 7075-T6 and 2024-T3 aluminum alloy specimens using the confocal microscope, the following conclusions can be made:

- The confocal microscope can be used effectively as a tool to quantitatively characterize fretting damage.
• The confocal microscope analysis of the specimen faying surfaces revealed at least three stages in the nucleation and the development of fretting damage leading to the final fracture of the specimens, viz. (1) formation of debris, (2) removal of materials, and (3) nucleation of fretting induced fatigue cracks and/or pits.

• For 7075-T6 aluminum alloy specimens, it was observed that the quantified fretting nucleated cracks were the smallest at 241 MPa (35 ksi) when compared to the two lower stress levels tested in this study. However, the material removal was found to be greater at higher stress levels when compared to lower stresses. From the confocal microscope analysis, it could be concluded that 7075-T6 specimens fractured because of fretting nucleated multiple cracks on the faying surface.

• For 2024-T3 specimens, the confocal microscope analysis of fretting damage suggest that fretting nucleated multiple pits are responsible for the final fracture of the specimen. Moreover, the quantified pit geometry revealed a correlation between the pit depth and pit dimension perpendicular to the applied load as well with the area of the pit.

Based on the pits observed in the confocal microscope upon completion of testing under three different loading conditions, the following conclusions can be made.

• The confocal microscope is a useful tool in pitting morphology study.

• Corrosion pits grown under fatigue loading conditions are larger than pits grown under sustained and zero loading conditions when produced on 7075-T6 aluminum alloy in 3.5% NaCl for a 24 hour period.

• Zero and sustained loading conditions produce pits of approximately the same size in cross sectional surface area.

• At a minimum, pits produced on 7075-T6 aluminum under fatigue conditions are 3 times larger in cross sectional area than those under zero and sustained loading conditions.

Several areas of future research have been identified as given below [11].

• Statistically based research should be performed so that these preliminary results can be confirmed and evaluated statistically.

• Further work should be conducted with the confocal microscope to enable 3D volumetric measurements and examination.

• Closer examination should be made into the mechanisms of fretting induced fatigue cracks and/or fretting induced pits. In addition, additional research should be performed to study the mechanism(s) of pitting corrosion because the results seem to indicate that pitting is not only an electrochemical phenomenon, but responds to mechanical environment.

• Further research should be conducted to examine the effects on grain orientation on loading scenario and corrosion pit size and shape.
ACKNOWLEDGMENT

The authors gratefully acknowledge the help of Dr. Ed King at the Biology Department, University of Utah in using the confocal microscope to analyze fretting and corrosion damage on the specimens. The support of FASIDE International, Inc. in conducting the research reported herein is greatly appreciated.

REFERENCES

Figure 1(a) -- Fatigue Specimen Configuration (All dimensions in mm).

Figure 1(b) -- Fretting Pad Configuration (All dimensions in mm).

Figure 1 -- *Test Specimen Configuration (Not drawn to scale).*
Table 1 -- Fretting fatigue test results and the confocal microscope analysis results

<table>
<thead>
<tr>
<th>Maximum fatigue stress</th>
<th>Number of fretting fatigue cycles</th>
<th>Observations using the confocal microscope</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7075-T6 Aluminum Alloy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>138 MPa (20 ksi)</td>
<td>51,000 cycles (test interrupted for analysis of damage)</td>
<td>A few black spots of debris</td>
</tr>
<tr>
<td></td>
<td>136,500 cycles (specimen fractured)</td>
<td>Observed cracks (crack length ranged from 20.64 µm - 72.05 µm)</td>
</tr>
<tr>
<td>172 MPa (25 ksi)</td>
<td>44,100 cycles (test interrupted for analysis of damage)</td>
<td>Observed debris (black color)</td>
</tr>
<tr>
<td></td>
<td>96,200 cycles (test interrupted for analysis of damage)</td>
<td>Observed material removal (depth varied from 3 - 10 µm)</td>
</tr>
<tr>
<td></td>
<td>128,400 cycles (test interrupted for analysis of damage)</td>
<td>Observed cracks (lengths varied from 20.99 - 169.06 µm) Observed two pits (pit depth of about 10 µm)</td>
</tr>
<tr>
<td>241 MPa (35 ksi)</td>
<td>35,500 cycles (specimen fractured)</td>
<td>Observed material removal (depth varied from 9 - 18 µm) Observed a couple of cracks (25.5, 35 µm)</td>
</tr>
<tr>
<td><strong>2024-T3 Aluminum Alloy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>207 MPa (30 ksi)</td>
<td>81,100 cycles (fractured)</td>
<td>Observed multiple pits (pit depth varied from 8 - 26 µm, pit dimension perpendicular to applied load varied from 10 - 39 µm, and pit area varied from 26 - 1478 sq. µm)</td>
</tr>
</tbody>
</table>
Stage I
Formation of debris [analyzed after 44100 cycles]

Stage II
Removal of material [after 96200 cycles]

Stage III
Nucleation of cracks [after 128400 cycles]

Figure 2(a) -- Digitized confocal images showing the stages in the nucleation and the development of fretting damage on the faying surface of 7075-T6 Aluminum alloy specimen (X20), $\sigma_{\text{max}} = 172$ MPa (25 ksi), $\sigma_n = 13.8$ MPa (2 ksi).

Figure 2(b) -- Digitized image showing fretting nucleated multiple pits on the faying surface of 2024-T3 aluminum alloy specimen (X20), (analyzed after fracture, 81100 cycles).
Direction of applied load

![Diagram showing pit geometry with dimensions](image)

**Figure 3** -- *Schematic showing pit geometry, where pit depth is Pd, pit dimension perpendicular to loading direction is PDy, and pit area is PA.*

(a) $\sigma_{\text{max}} = 241 \text{ MPa (35 ksi)}$  
(b) $\sigma_{\text{max}} = 172 \text{ MPa (25 ksi)}$,  
(c) $\sigma_{\text{max}} = 138 \text{ MPa (20 ksi)}$,  
(crack length 25.5 $\mu$m)  
(crack length = 169 $\mu$m)  
(crack length = 20 - 72 $\mu$m)

**Figure 4** -- *Digitized confocal images showing the size of fretting nucleated cracks at different maximum fatigue stress levels on the faying surface of 7075-T6 aluminum alloy (X20).*
Figure 5(a) -- Depth of material removal 12 - 18 µm.

Figure 5(b) -- Depth of material removal 5 - 9 µm.

Figure 5 -- Digitized confocal images showing material removal on 7075-T6 faying surface (X20), $\sigma_{\text{max}} = 241 \text{ MPa (35 ksi)}$, $\sigma_{n} = 13.8 \text{ MPa (2 ksi)}$, $R = 0.1$, $f = 10 \text{ Hz}$, 
Laboratory air.
Figure 6 -- *Graph of crack length vs. maximum fatigue stress, Material: 7075-T6 aluminum alloy, $\sigma_n = 13.8$ MPa (2 ksi), Environment: Laboratory air.*

Figure 7 -- *Graph of depth of material removal vs. maximum fatigue stress, Material: 7075-T6 aluminum alloy, $\sigma_n = 13.8$ MPa (2 ksi), Environment: Laboratory air.*
Figure 8 -- Digitized confocal image of 2024-T3 faying surface revealing multiple pits (X20), $\sigma_{\text{max}} = 207 \text{ MPa (30 ksi)}$, $\sigma_n = 13.8 \text{ MPa (2 ksi)}$, $R = 0.1$, $f=10 \text{ Hz}$, Laboratory air.

![Digitized confocal image of 2024-T3 faying surface revealing multiple pits (X20)](image)

Figure 9 -- Correlation between pit depth and pit area, Material: 2024-T3 aluminum alloy, $\sigma_n = 13.8 \text{ MPa (2 ksi)}$, $\sigma_{\text{max}} = 207 \text{ MPa (30 ksi)}$, Environment: Laboratory air.

![Correlation between pit depth and pit area](image)
Figure 10 -- Correlation between pit depth and pit dimension perpendicular to applied load, Material: 2024-T3 aluminum alloy, $\sigma_n = 13.8$ MPa (2 ksi), $\sigma_{\text{max}} = 207$ MPa (30 ksi), Environment: Laboratory air.

Figure 11 -- Close view of specimen in environmental chamber (1. specimen, 2. environmental chamber, 3. clamps, 4. inlet hose, 5. outlet hose).
Figure 12. -- Close view of sustained load setup (1. environmental chamber, 2. grip, 3. clamps, 4. inlet hose, 5. outlet hose, 6. drain tray).

Figure 13 -- Close view of fatigue load setup of specimen in environmental chamber and grips (1. environmental chamber, 2. clamp, 3. grip, 4. actuator arm, 5. load cell, 6. drain tray, 7. inlet hose, 8. outlet hose).
Figure 14 -- *Digitized image of a pit from zero load specimen with confocal microscope (60X).*

Figure 15 -- *Digitized image of pit #4 from fatigue load specimen taken with the confocal microscope (40X).*
Figure 16 -- Digitized image of pit #5 from fatigue load specimen taken with the confocal microscope (40X).

Figure 17 -- Digitized image of pit #2 from fatigue load specimen taken with the confocal microscope (40X).
Figure 18 -- Digitized image of pit #3 from fatigue load specimen taken with the confocal microscope (40X).

Figure 19 -- Digitized image of a pit from sustained load specimen taken with the confocal microscope (40X).
Figure 20 – *Photograph of a pit from a fatigue load specimen (Etched, 800X).*

Table 2 -- **Summary of Pit Areas as Determined by the Confocal Microscope**

<table>
<thead>
<tr>
<th>Load Type</th>
<th># Pixels</th>
<th>Pixel Length</th>
<th>Pit Area (µm²)</th>
<th>Size Comparison for Load Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero</td>
<td>70</td>
<td>0.247</td>
<td>4.27</td>
<td>Smallest</td>
</tr>
<tr>
<td>Zero</td>
<td>1569</td>
<td>0.247</td>
<td>95.75</td>
<td>Largest</td>
</tr>
<tr>
<td>Sustained</td>
<td>271</td>
<td>0.247</td>
<td>16.54</td>
<td>Smallest</td>
</tr>
<tr>
<td>Sustained</td>
<td>1146</td>
<td>0.247</td>
<td>69.94</td>
<td>Largest</td>
</tr>
<tr>
<td>Fatigue</td>
<td>4720</td>
<td>0.274</td>
<td>288.05</td>
<td>Smallest</td>
</tr>
<tr>
<td>Fatigue</td>
<td>78585</td>
<td>0.370</td>
<td>10763.88</td>
<td>Largest</td>
</tr>
</tbody>
</table>