Evaluation of nondestructive testing methods for the detection of fretting damage

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Abstract

Experiments have been carried out to determine the viability of using nondestructive testing (NDT) techniques to detect active fretting processes and detect the presence of fretting damage on the faying surfaces of aircraft fuselage joint structures. A number of small specimens representing an element of an aircraft fuselage joint were subjected to fatigue, monitored during loading and inspected after loading, to determine the ability of various NDT techniques to detect fretting damage. These specimens were composed of two sheets of Al 2024-T3 fastened together with rivets, and the fretting damage expected to occur on hidden surfaces of this structure.

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1. Introduction

Although fretting is believed to be a significant source of fatigue crack nucleation, there is very limited literature on the subject of using NDT to detect fretting. Significant recent efforts at the University of Dayton Center for Materials Diagnostics [1–3] have been directed at studying fretting fatigue in aerospace engine alloys, specifically Ti–6Al–4V. Optical and acoustic microscopy based methods have been used to characterize fretted surfaces. In the above work, all fretted surfaces were exposed for the purposes of the study. While the results of this work were generally successful, it is not apparent how these methods could be applied to hidden surfaces.

Thermography has also been used on exposed fretted surfaces to attempt to measure fretting damage [4]. Remote field eddy current inspection method has been used to measure material lost to fretting in a condenser tube-support plate structure, in a laboratory setting [5]. Ultrasonic methods have been used to measure surface roughness on the far surface of thin sheets of aluminum, which may be applicable to the detection of fretting damage [6].

The authors are not aware of any literature specifically concerning NDT for fretting on hidden surfaces, such as on the faying surfaces of lap joints or in the bore of fastener holes. There are NDT techniques which are theoretically promising for the detection of fretting on hidden surfaces in controlled test situations. Acoustic emission testing (AET) practitioners have gone to some lengths to distinguish between fretting and crack growth, and therefore AET may be useful in a controlled situation. Passive thermal imaging in situ may be able to detect heat caused by fretting, and is investigated in this paper.

Eddy current, pulsed eddy current, ultrasonic, and radiography techniques were used to attempt to detect and measure fretting damage on selected test coupons after cyclic loading. Passive thermal imaging was used on the coupons during cyclic loading to attempt to detect the fretting process in action.
2. Theory

2.1. Fretting

A brief description of fretting is provided in the following section. The following is derived largely from Ref. [7], with permission from the authors.

Fretting is a wear phenomenon that occurs between two mating surfaces: it is adhesive in nature, and vibration is its essential causative factor. Frequently fretting is accompanied by corrosion. In general, fretting occurs between two tight fitting surfaces that are subjected to a cyclic, relative motion of extremely small amplitude. Fretted regions are highly sensitive to fatigue loading leading to crack nucleation. Under fretting conditions, fatigue cracks can nucleate even at stresses in the fretted structure that are lower than the endurance limit, often resulting in structural failure that occurs at much fewer cycles than anticipated. Nucleation of fatigue cracks in fretted regions depends mainly on the state of stress on the surface and particularly on the stresses superimposed on the cyclic stress. The time to nucleation of cracks can be significantly reduced as a result of fretting. Common sites for fretting are in joints that are bolted, keyed, pinned, press fitted, and riveted. These sites are common in the assembly of most air vehicles, ground vehicles, power plants, equipment, and machinery.

Fretting damage is differentiated by three distinct modes: fretting wear, gross sliding wear, and fretting fatigue. Fretting wear, which occurs for relatively small vibratory motion, normally results in relatively little damage and rarely causes premature structural failure. Gross sliding wear, which occurs for relatively large vibratory motion, normally results in visual surface damage, but rarely causes premature structural failure. Fretting fatigue, caused by intermediate vibratory motion, is the most damaging, causing cracking and often resulting in premature structural failure.

2.2. Nondestructive testing

The NDT methods evaluated for fretting detection are described in the following sections.

2.2.1. Eddy current NDT

Eddy current NDT methods are the most widely used NDT methods in the aerospace sector. In general, they involve measuring magnetic flux or magnetic fields generated by inducing currents in the test article. The currents are induced by creating time-varying currents within a coil near the test article, and the resultant flux can be measured by coils or resultant fields measured by magnetic field sensors such as Hall effect or magnetoresistive sensors.

Eddy current techniques are sensitive to bulk material properties of conductivity and permeability, as well as local changes or discontinuities in these properties as caused by features such as cracks, pits, or boundaries. For more information on eddy current NDT, see Ref. [8].

2.2.2. Ultrasonic NDT

Ultrasonic NDT is also common in aerospace. The term ultrasound refers to sound (i.e. mechanical vibrations) of frequencies greater than 20 kHz, which is approximately the limit of human hearing. Most NDT work is done between the frequencies of 1 MHz and 10 MHz, which results in wavelengths of the order of 1 mm in common engineering materials.

Ultrasonic energy is transmitted into the object under test, and the same transducer or another can be used to monitor the returned energy. The velocity and attenuation of ultrasonic waves are directly related to certain material properties, and interfaces within the object under test can also be imaged. For more information on ultrasonic NDT, see Ref. [9].

2.2.3. Radiographic NDT

Film-based X-ray radiography was used in this project. The object under test is placed between an X-ray source and a film, and the source is enabled for a set time and energy to expose the film. X-rays are absorbed increasingly by atoms with increasing atomic number, so the resulting images on film show changes in material and in thickness as changes in intensity. For more information on radiographic NDT, see Ref. [10].

2.2.4. Thermographic NDT

The following is an explanation of the theory of thermography as applied to nondestructive inspection. Due to its importance in this work, a more in-depth review is provided than for other NDT techniques. Further information can be found in Refs. [11,12].

In thermographic NDT, the infrared (IR) spectrum is used to map the surface temperature of the inspected specimen. In general, some source of energy is used to create a temperature difference between the specimen and the surrounding environment, and the heat flow is monitored as the specimen returns to thermal equilibrium. Variations in structure or material properties result in variations in heat flow and the surface temperature. The most useful wavelengths are between 0.7 and 20 μm. The energy emitted by the specimen depends on its temperature and on photon’s wavelength.

Pulsed thermography is defined as thermography where energy is applied to the specimen using a pulsed excitation. The duration of the excitation varies from a few milliseconds for good thermal conductor to a few seconds for low-conductivity material. The excitation source can be a flash lamp, laser, hot air flow, cold air flow, or any other source or sink of thermal energy. The source can be warm or cold with respect to the surrounding environment; it does not matter since the important point in thermography is the propagation of a thermal wave into the material. After the excitation, the surface temperature increases (in
the case of warm excitation) and decreases due to thermal diffusivity loss and convection loss from the environment. The thermal diffusion is affected by the presence of discontinuities in the structure or changes in material properties. These discontinuities change the propagation of the thermal wave and cause a temperature difference between different areas.

When a thermal wave traverses an interface from a layer of high conductivity to a layer of lower conductivity, there is an accumulation of energy above the low conductivity media. Thus, the temperature above a defective area increases compared to the temperature above a sound area. Fig. 1 presents the typical thermal wave propagation in a specimen during thermographic inspection.

The thermal propagation time depends on the thickness of the material (z) and its thermal diffusivity (α):

\[ t \approx \frac{z^2}{\alpha} \]  

where the thermal diffusivity (\( \alpha \)) is defined by

\[ \alpha = \frac{k}{c\rho} \]

where \( k \) is the thermal conductivity, \( c \) is the specific heat and \( \rho \) is the density.

These equations can be used to estimate the depth of discontinuities. Eq. (1) is one-dimensional, and requires knowledge of the thermal properties of the item under inspection. In complex structures, it is usually more practical to use calibration specimens to determine depth.

Stepped heating and lock-in thermography are other thermographic techniques. Stepped heating consists of heating a specimen and monitoring the evolution of the surface temperature. In lock-in thermography, periodic heating is applied to the specimen. The heat source is usually a lamp or laser. The temperature variations in the steady-state regime are then monitored [13]. Lock-in thermography is more time consuming than pulsed thermography, however, it allows detection of deeper discontinuities.

2.2.4.1. Thermoelastic effect. The internal energy of a body depends both on temperature and deformation. Time-varying deformation of the body changes temperature, and vice versa. The science of thermoelasticity is the study of this coupled phenomena [14].

The thermoelastic effect describes the generation of heat in a material under externally applied stress. This effect is likely occurring on the same time scale with any fretting damage in the test specimens. To evaluate fretting damage via thermography, the data acquisition must be synchronized with the applied stress. Temperature variations due to the thermoelastic effect are expected to show a frequency variation similar to the applied stress, while temperature variations due to the stick/slip fretting process are not expected to be simply correlated with the frequency of applied stress. These assumptions are discussed in Section 5.

3. Experiment

3.1. Materials and apparatus

The goal of the experiments was to assess the ability of thermography to detect fretting on the faying surface of an aircraft fuselage joint in a controlled test environment. A simple riveted two-layer specimen of Al 2024-T3 was used to provide a simple and economical test specimen that would experience fretting damage similar to a larger fuselage joint specimen. Photographs of a specimen are shown in Figs. 2 and 3.

Each specimen was made of two sheets, of 6 in. (152.4 mm) length, 1 in. (25.4 mm) width and a thickness of 0.063 in. (1.6 mm), of Al 2024-T3 clad material. The two sheets were overlapped by 2.75 in. (69.85 mm), and fastened by three rivets. The rivets were 0.1565 in. (3.975 mm) in diameter, of Al 2117, installed at a 1 in. pitch. A CAD drawing of the standard specimen is presented in Fig. 4.

The design of the specimens remained constant throughout experimentation, with the exception of changing the riveting method from displacement-controlled to force-controlled (squeeze force of 18 kN (4046 lbf) at 25 lb/s). The effects of this change are discussed below. The specimens are painted because the low emissivity of the bare Al surface makes thermography difficult.

The thermography results were obtained using an Echotherm, a commercial thermographic system designed by
thermal wave imaging [15]. This system is composed of an illumination head, a control system, power supplies and a computer. The illumination head is a closed hood in which two xenon flash lamps and flash reflectors are positioned. A LCD monitor provides a live image of the IR camera output. The IR camera used for the inspections was a ThermaCAM SC 3000 by Flir Systems [16]. This camera is a quantum well infrared photo detector (QWIP), which has a focal plane array detector of $320 \times 240$ elements, a thermal sensitivity of 20 mK at 303 K and a spectral response from 8.0 to 8.8 $\mu$m.

The specimens were cycled in an MTS load frame, that has a load cell capacity of 22,000 lbs, utilizing hydraulic grips and controlled by a TestStar controller. A black cloth canopy was draped over the frame, in order to eliminate outside sources of thermal radiation. Also, a supply of compressed air was used to cool down the lower grip of the load frame, as it was found to be producing heat measurable on the passive thermal imaging of the specimens during loading.

3.2. Test procedure

The specimens were installed in the load frame and the thermography camera was set up to observe the painted
side. Constant amplitude cycling, with marker band cycles on a subset of specimens, was applied at 10 Hz, first from 20 to 800 lbs of force, then from 20 to 900 lbs after the riveting method of the specimens was changed slightly. The specimens were cycled for one of two lengths of time: either until failure, or until examination of the thermography data suggested the first phases of fretting were occurring. Initially, the procedure was to first cycle the specimen for only 500 cycles, while recording images at 60 Hz. This was done to obtain a higher resolution observation of the initial cycling, as it appeared that the most significant results were being obtained here. Following this, the specimen was run for blocks of 33,300 cycles, with images being taken at 1 Hz. The number of cycles was determined by how many images the EchoTherm software could store in the computer buffer before requiring a brief downtime to save the data. The slower image acquisition speed was to conserve computer memory, as each block of cycling takes up roughly 300 MB of hard drive space. Thus, it was advantageous to slow down the acquisition as much as possible while retaining enough temporal resolution.

For the last six coupons, the procedure was modified to introduce a special loading sequence that was used to mark the fracture surface for post-fracture study. The presence of the marker bands made it possible to determine crack shape and size at specific points in specimen life and to determine the sensitivity of the thermal imaging as a function of crack size. The loading sequence used has been applied in various forms by a number of researchers [17–19].

The basic sequence used blocks of 2000 cycles at the primary fatigue test load separated by marker blocks of four, six, and 10 bands. One pass through the spectrum contained 8170 cycles. Once spectrum pass is shown in Fig. 5, and the typical appearance of the bands as viewed under a light microscope is shown in Fig. 6. The space between the sets of ten and four marks in Fig. 6 represents the 2000 constant amplitude cycles applied between marker sets. The marker sets themselves are applied at the same stress ratio as the primary load cycles. The marks are comprised of alternating 100 cycles of underload (80% of the peak cyclic test stress) with 10 cycles of peak load. A set of 10 marks gets its appearance from 10 100-cycle underload groups (see Fig. 5).

4. Results

A synopsis of the results is given in this section. Complete description and relevant data images are described in the Appendix of Ref. [20]. For this fretting study, 17 coupons were used. Note that some of the specimens in the numbered series (2, 4, 5 and 14) were used for a study of riveting pressure, and were not used for the fretting study. Specimen 1 was used to test the load frame programming and thermography data acquisition, but was not of the exact same construction as the other specimens, so it is not considered in the results. The results are summarized in Table 1.

4.1. Results – fretting damage

The results suggest that for this specimen configuration and loading, fretting first occurs on the interface between the fastener and the bore, very early in life, and is followed very soon by fretting damage on the faying surface. All specimens showed signs of fretting damage. Specimens 12 and 20 show signs of fretting on the top fastener and bore after only 252 and 100 cycles, respectively (Fig. 7) but no damage on the faying surfaces. Specimen 13 after 67 cycles did have damage on both the top fastener and bore as well as on the faying surface.

Damage on the faying surfaces of the two sheets occurs after damage on the fastener and bore, but still very early in the life of the coupons. Fig. 8 shows fretting damage on specimen 13, the top sheet, top hole faying surface after only 67 cycles. Fretting damage was visible on the fastener and bore also. Fig. 9 shows an example of fretting damage on the fastener.

The amount of fretting damage on the faying surfaces was measured by area, and this correlates well with the number of cycles (Fig. 10). Only the data from the coupons riveted with force control are included here, as they are believed to be more consistent than displacement control riveting. To estimate the fretting areas, the photograph of each specimen was imported into a photo editor software. Fretting products is seen has black residues on the faying surface (Fig. 8), and a threshold was selected to isolate these black areas from the rest of the faying surfaces. The software has a function that counts the number of pixels above the selected threshold. Then, for each specimen the number of pixels was converted to surface area units (mm^2). The conversions were performed by calculating the number of pixels per mm based on known physical sizes of the rivet holes and the coupons and their pixel size in the images.
4.2. Results – NDE after testing

Ultrasonic inspections (UT) were performed on selected specimens after testing and disassembly. The inspections

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Fretting on fastener and/or bore</th>
<th>Fretting anywhere on faying surfaces</th>
<th>Fretting area around top fastener hole (mm²)</th>
<th>Total number of cycles applied</th>
<th>Cycled to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>81,395</td>
<td>y</td>
</tr>
<tr>
<td>3</td>
<td>y</td>
<td>y</td>
<td>2</td>
<td>172,358</td>
<td>n</td>
</tr>
<tr>
<td>6</td>
<td>y</td>
<td>y</td>
<td>1.45</td>
<td>340,760</td>
<td>n</td>
</tr>
<tr>
<td>*7</td>
<td>y</td>
<td>y</td>
<td>0.74</td>
<td>5,000</td>
<td>n</td>
</tr>
<tr>
<td>8</td>
<td>y</td>
<td>y</td>
<td>0.4</td>
<td>3,256</td>
<td>n</td>
</tr>
<tr>
<td>9</td>
<td>y</td>
<td>y</td>
<td>0.86</td>
<td>5,000</td>
<td>n</td>
</tr>
<tr>
<td>10</td>
<td>y</td>
<td>y</td>
<td>3.14</td>
<td>147,700</td>
<td>y</td>
</tr>
<tr>
<td>11</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>564,704</td>
<td>y</td>
</tr>
<tr>
<td>12</td>
<td>y</td>
<td>n</td>
<td>0</td>
<td>252</td>
<td>n</td>
</tr>
<tr>
<td>13</td>
<td>y</td>
<td>y</td>
<td>2.041</td>
<td>67</td>
<td>n</td>
</tr>
<tr>
<td>14</td>
<td>y</td>
<td>y</td>
<td>2.48</td>
<td>439</td>
<td>n</td>
</tr>
<tr>
<td>15</td>
<td>y</td>
<td>y</td>
<td>0.75</td>
<td>339,355</td>
<td>n</td>
</tr>
<tr>
<td>16</td>
<td>y</td>
<td>y</td>
<td>5.79</td>
<td>464,387</td>
<td>y</td>
</tr>
<tr>
<td>17</td>
<td>y</td>
<td>y</td>
<td>7.71</td>
<td>372,746</td>
<td>y</td>
</tr>
<tr>
<td>18</td>
<td>y</td>
<td>y</td>
<td>6.88</td>
<td>202,945</td>
<td>y</td>
</tr>
<tr>
<td>19</td>
<td>y</td>
<td>y</td>
<td>4.23</td>
<td>100</td>
<td>y</td>
</tr>
<tr>
<td>20</td>
<td>y</td>
<td>n</td>
<td>0</td>
<td>3,000</td>
<td>n</td>
</tr>
<tr>
<td>21</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>81,395</td>
<td>n</td>
</tr>
</tbody>
</table>

? Misplaced specimen.
* No thermography data taken.
Thermography inspection from the backside.
Displacement control rivetting.
Marker bands.

Fig. 7. A photograph of the top surface, top hole of specimen 12 after 100 cycles. The black areas visible in the countersink are due to fretting damage.

Fig. 8. A photograph of specimen 13 the top sheet, top hole faying surface after 67 cycles. Fretting damage is visible around the bottom of the hole as black areas.

4.2. Results – NDE after testing

Ultrasonic inspections (UT) were performed on selected specimens after testing and disassembly. The inspections
were performed with the UT transducer on the outer surface, to simulate what would be required in a realistic inspection situation. A 25 MHz focused transducer was used in immersion to perform conventional normal incidence, longitudinal wave, pulse-echo inspections. Although machining marks and deformations around the holes due to riveting and rivet removal are easily visible in the UT results, no indications that could be uniquely identified as due to fretting damage were found. An example of an ultrasonic amplitude image, and a photograph of the corresponding section of specimen 10, are shown in Fig. 11 below. It is unlikely that UT methods will be practical for inspection for fretting damage on hidden surfaces; as the physical sizes of the fretting damage are on the order of the size of machining marks, deformation from assembly, and wear from handling.

Eddy current, pulsed eddy current radiographic and pulsed flash thermography inspections of the individual sheets from specimen 7 were performed from the outer surfaces. No indications were found of the fretting damage in these inspections.

Fig. 9. A photograph of the rivet from the top hole in specimen 10, showing fretting damage around the countersink.

Fig. 10. A plot of the fretting damage on the faying surface of the top hole of the specimens manufactured using force control riveting, as a function of the number of cycles tested.

Fig. 11. An ultrasonic amplitude image (left) and the photograph of the corresponding section of specimen 10.
4.3. Results – thermography monitoring during testing

The IR camera was used to monitor the tests described in this paper while cyclic loading was underway. Raw thermal images of many of the specimens showed the appearance of hotter areas on either side of the top rivet, including all of the force control riveted specimens which were observed from the side of the top sheet. When the time derivative of the thermal image sequence was observed, similar “hot spots” were observed around rivets in all except two specimens which were imaged from the bottom sheet. Examples of the raw thermal data (for specimen 10 at 10 cycles) and thermal time derivative data (for specimen 16 at 3 cycles) are shown in Fig. 12 and Fig. 13 respectively. The thermography results showing the intensity variation and number of cycles before the hot spots were detected are summarized in Table 2.

![Fig. 12. The raw thermal image of specimen 10 at 10 cycles, showing hot areas on either side of the top and middle rivets.](image)

![Fig. 13. The time derivative image of specimen 16 after 3 cycles, showing an anomalous area on either side of the top rivet.](image)

**Table 2**
A summary of the thermography results for the specimens used in the fretting study

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Heat signature detected on raw data?</th>
<th>Delta T (intensity)</th>
<th>Time to hot spot (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>y</td>
<td>15</td>
<td>39,001</td>
</tr>
<tr>
<td>3</td>
<td>y</td>
<td>5</td>
<td>343</td>
</tr>
<tr>
<td>6</td>
<td>n</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>8</td>
<td>y</td>
<td>7</td>
<td>60</td>
</tr>
<tr>
<td>9</td>
<td>y</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>y</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>n</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>12</td>
<td>n</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>13</td>
<td>n</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>14</td>
<td>n</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>15</td>
<td>n</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>16</td>
<td>y</td>
<td>12</td>
<td>279,136</td>
</tr>
<tr>
<td>17</td>
<td>y</td>
<td>14</td>
<td>441,876</td>
</tr>
<tr>
<td>18</td>
<td>y</td>
<td>13</td>
<td>369,101</td>
</tr>
<tr>
<td>19</td>
<td>y</td>
<td>10</td>
<td>191,241</td>
</tr>
<tr>
<td>20</td>
<td>y</td>
<td>7</td>
<td>26</td>
</tr>
<tr>
<td>21</td>
<td>y</td>
<td>6</td>
<td>24</td>
</tr>
</tbody>
</table>

Thermography inspection from the backside.
Displacement control riveting.
Marker bands.
Later on in the life of the specimens, cracks were observed in each case originating from the top hole. It is well known that crack tips can be excited with an external mechanical vibration and imaged thermally [21], and this effect is observed in all the specimens which were loaded to failure. Fig. 14 below shows three raw thermal images showing the progression of the crack in specimen 10. The number of cycles is, from left to right, 143,000, 145,000, and 147,000.

The thermoelastic effect was also observed in all of the thermography sequences taken at high enough acquisition rates: 5 or 10 Hz loading frequencies resulted in 5 or 10 Hz temperature variations across the specimen. This effect can be calibrated to yield strain measurements, but in this work was an additional extraneous variable on top of the heat signatures expected from fretting. The high frequency of thermal data acquisition in the early stages of the experiments was used to distinguish between thermoelastic effects and other heat sources.

For each sequence of acquisition, the average of 10 frames was computed. Then, a local average of 5 × 5 pixels at the hot spots location was compared with an average of 5 × 5 pixels elsewhere on the specimen. The difference between these two averages was named delta $T$ and represents the intensity variation between these areas. These intensity values correspond to the energy flux received by the infrared camera and is related to the temperature of the object imaged. The presence of hot spots was detected and remained constant until the coupons enter the crack propagation regime; moment at which the delta $T$ value increases and the hot spots start progressing in the direction outward to the rivet hole as seen in Fig. 14. The value of the delta $T$ measured and the time in number of cycles it took for them to be visible are presented in Table 2. It was found that the measured temperature difference between the “hot spots” and the surroundings (delta $T$) correlated to the area of fretting damage (Fig. 15), another indication that fretting is responsible for the signal.

Four specimens, 16–19, were cycled to failure with marker band sequences included in the loading. This allowed the estimation of the evolution of crack size with loading, and matching of the thermal imaging of the cracks to their size. After the coupons 16 and 19 failed, the fracture faces were examined under a Nikon MM-60 light microscope to reconstruct crack growth history and crack shapes from marker bands. The scope is equipped with extra-long working distance objectives capable of magnifications ranging from 50× to 1000×. The microscope is also equipped with 0.5-micron resolution X–Y–Z encoded axes for making precise measurements.

To create the crack growth history, the last marker band in the sequence (just prior to failure) was located,

![Fig. 14. Raw thermal images of specimen 10 during loading, at from left to right, 143,000, 145,000, and 147,000 cycles. The tips of the cracks are visible as bright spots on either side of the top rivet.](image)

![Fig. 15. A plot of the difference in apparent temperature (arbitrary units) between the detected hot spots and the surrounding area, as a function of the fretting damage measured after teardown.](image)
and then each previous mark was tracked back towards the crack origin until marks could no longer be observed (ease of marker detection is highly dependent on many factors to include grain orientation, stress intensity, and presence of oxide from fretting). The marker bands were first tracked along a line close to the specimen faying surface, then select marker bands were chosen for further reconstruction where the full crack front was traced to generate crack shape. It was necessary to locate all intermediate bands first to have confidence in the cycle count corresponding to the fully-traced crack fronts (Fig. 16 and 17). A sample crack growth curve for Specimen 19 is shown in Fig. 18.

The fully traced crack fronts were used to correlate crack size with the NDI signals observed at corresponding specific times during the test.

The chart for specimen 16 summarizing the crack growth as a function of cycles, determined by marker band analysis, is shown in Fig. 16 below. The crack was detected on the raw thermography data at 279,136 cycles and on the processed thermography data at 271,000 cycles, at which time the crack was approximately at the edge of the countersink. The complete data from the marker band analysis is shown in Table 3.

The chart for specimen 19 summarizing the crack growth as a function of cycles, determined by marker band analysis, is shown in Fig. 17 below. The crack was detected on the raw thermography data at 191,241 cycles and on the processed thermography data at 181,000 cycles, at which time the crack was only just breaking the top surface, but was a few millimeters long on the bottom surface.
5. Conclusion

Various nondestructive testing (NDT) methods were evaluated for their potential to detect fretting damage on the faying surfaces of intact specimens representing aircraft fuselage joint construction. Thermal imaging was used to monitor these coupons while they were subject to fatigue. Ultrasonic, eddy current, thermography, and radiographic NDT were used to inspect the coupons after fatigue loading.

Only the thermal imaging of the specimens during testing was able to identify fretting damage in all cases. Ultrasound methods showed some promise, but could not distinguish between fretting and other damage such as machining marks or wear from general handling and use. This likely makes UT impractical in field situations.
The specimens were fatigued to various cycle counts in order to attempt to understand the fretting process. In all specimens, fretting damage was observed. Fretting occurs first on the rivet/bore interface, but fretting damage on the faying surfaces begins soon thereafter. Damage accumulation in terms of area is very rapid at low cycle counts, continuing to increase but at a much reduced rate throughout the specimen life.

In all specimens which were observed from the top sheet, either the raw thermal images or the slope thermal images (a time derivative of the raw data) showed areas that were hotter on both sides of the top rivet than their surroundings. Only in two of five specimens observed from the bottom sheet were hot spots observed. These hot spots showed up early in life, and in most cases remained until crack tip signatures were observed.

Four specimens, 16–19, were cycled to failure with marker band sequences included in the loading. This allowed the estimation of the evolution of crack size with loading, and matching of the thermal imaging of the cracks to their size. Marker band analysis was performed by AP/ES Inc. for specimens 16 and 19.

The key difficulty in interpreting the results is the lack of specimens that had no fretting damage. Without this type of data, it is difficult to affirm that it is the fretting damage responsible for the hot spots on the thermal images. The area on either side of the top rivet, where the hot spots were located, is also the area of maximum stress. Therefore the thermoelastic signal in this area will also be higher than in surrounding regions. In order to determine the cause of the hot spots, thermal imaging was performed at high frequencies on numerous specimens. The frequency of loading was apparent in all images, and the magnitude of the thermal cycling with the load was larger at the hot spots as would be expected.

Specimens 11–15 were tested the same as the other specimens, except that the thermal camera imaged the bottom sheet of the specimen during loading. In only two of these five were hot spots seen. This suggests that the fretting damage may have been more severe nearer to the other surface, which may be happening at the rivet/hole countersink interface. This also suggests that the thermoelastic effect is not strong enough to generate the observed hot spots, as there also will be elevated stress levels and thus thermoelastic heating around the holes on the bottom sheet.

Sonically excited thermography may be able to distinguish between areas with and without fretting, by exciting further fretting and measuring a resulting localized heating. It will be subject of future work. Also of interest for future effort is the effect of the strain, present while the coupon is under load, on the thermography results.

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