Evaluation of some parameters influencing vibrothermographic crack heating

Tyler Joseph Lesthaeghe
Iowa State University

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Evaluation of some parameters influencing vibrothermographic crack heating

by

Tyler Joseph Lesthaeghe

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Engineering Mechanics

Program of Study Committee:
Stephen D. Holland, Major Professor
Ashraf Bastawros
Hridesh Rajan

Iowa State University
Ames, Iowa
2015

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Vibrothermography is a nondestructive testing technique that uses vibration-induced heating to locate cracks inside parts. Industrial application of vibrothermography has typically been limited due to a lack of complete understanding of the factors influencing vibrothermographic crack heating. In other words, in otherwise identical circumstances, some cracks heat differently. This thesis presents modified versions of three journal papers related to developing a predictive forward model of the vibrothermography process. The first paper discusses an empirical model for vibrothermographic crack heating, including factors for vibrational amplitude, crack mobility and crack closure. The paper provides details of the model and the data collection process. This paper also demonstrates a method for measuring crack closure with vibrothermography. An accompanying appendix also provides complete experimental results. The second paper describes an unexpected increase in crack heating after introducing a lubricating oil into a crack. It was also discovered that the amount of increase in heating decreases as excitation amplitudes are increased, to the point that, at high excitation amplitudes, overall crack heating may decrease. A proposed hypothesis is presented. A third paper discusses a tool developed to help manage and interpret the large quantities of data collected during this work. Databrowse is an extensible web-based platform for viewing, querying, and transforming laboratory data. The details of the system and our experiences are provided.
CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

Vibrothermography is a promising nondestructive evaluation (NDE) technique that utilizes vibration induced heating to locate cracks and other defects in materials. Originally discovered by Henneke, et al. in the late 1970’s [1], several groups have since expanded and continued to refine the technique, also known as sonic IR or thermosonics. Work in the early 2000’s, initiated by Han, et al., has improved the technique by introducing high quality infrared cameras and improved vibrational excitation methods [2].

Figure 1.1 displays a visual representation of the three physical processes making up vibrothermography. The first process, Figure 1.1a, involves the introduction of vibrational energy into a part. The work of Han, et al. popularized the use of a 20 kHz ultrasonic welder as the excitation source. The welder is coupled to the specimen with a soft material resulting in the excitation of many harmonics and sub-harmonics within the specimen [2]. The technique, dependent on acoustic chaos, introduces challenges with repeatability and reliability, two of the major factors limiting the industrial deployment of vibrothermography.

Since then, excitation utilizing a broadband PZT-based transducer has been developed that can target specific resonance frequencies within a part, resulting in much more predictable behavior [3]. Using this type of transducer, the specimen is first excited with a broadband frequency sweep and vibration is captured utilizing a laser vibrometer. The
target resonance frequency is identified and subsequent measurements are performed by performing a tone burst at that specific frequency. The work presented in this thesis utilizes this technique.

The second physical process, seen in Figure 1.1b, is the conversion of vibrational energy to crack heating. The crack heating mechanism is not fully understood. While there are ongoing debates related to the mechanisms [4; 5; 6], increasing evidence suggests that a friction rubbing or adhesion hysteresis between contacting crack asperities is the dominant mechanism for crack heating [7].

The third physical process, seen in Figure 1.1c, is the flow of heat from the crack to the surface, where it is imaged by an infrared camera. The physics of heat flow are much better understood, in comparison to the previously mentioned challenges with vibration and heat flow. Much of the work related to heat flow with respect to vibrothermography center around development of techniques to improve sensitivity of measurement with appropriate image processing or physics-based reconstruction [8; 9].

The work presented in this thesis is a part of a broader effort toward developing a physics-based forward model of the vibrothermography process. The end goal is a predictive model capable of being applied toward a model-assisted probability of de-

\footnote{Figure courtesy S. Holland}
tection (POD) study. A POD study provides quantified information on the reliability of a particular capability and is a critical step toward further industrial application of thermography.

As mentioned, challenges related to repeatability have prevented broad adoption of vibrothermography. Specifically, some cracks, under otherwise identical conditions, can produce different amounts of heat. This thesis will present an attempt to better understand these behaviors and seek to identify and resolve variability in vibrothermography.

1.2 Thesis Organization

This thesis presents modified forms of three papers being prepared for submission. All three papers consider some aspect of the work performed as a part of the broader modeling effort.

The first paper discusses the modeling of the crack heating mechanism. An empirical model was chosen, as explicit modeling is likely not possible and finite element modeling (FEM), while likely possible, will tend to introduce too many free parameters to have predictive utility. FEM has been limited to qualitative studies at present [10]. The paper defines a proposed model and details the measurement process utilized to collect the significant quantity of data required to fit the model parameters. (This work was a long term collaborative effort with this author playing a primary role in specimen fatigue, experimental data measurement, and data post processing efforts and supporting roles in the other efforts described.)

The second paper discusses a simple experiment originally performed in an attempt to better understand some of the underlying physical mechanisms behind crack heating. In this work, a lubricating oil was introduced into the crack with the intent of reducing surface energies and inhibiting the frictional effect or adhesion hysteresis effect. However, crack heating unexpectedly increased after the introduction of oil. The details of this
experiment and some potential proposed explanations are presented. (This author was the primary person responsible for this effort, with feedback and support provided by the other named authors.)

The third paper discusses a tool developed to better manage and view the large experimental data sets collected as a part of this modeling effort. Databrowse is an extensible web based platform for the viewing and transforming of laboratory data sets. It played a critical role in the analysis of the experimental data set collected during this work. The details of how the system work and our experiences using it are presented. (This author was the primary person responsible for this effort, with feedback and support provided by the other named author.)

The final chapter of this thesis presents some overall conclusions and final thoughts. An appendix is provided with the details of the experimental data set and plots are shown that provide a convenient representation of the entire data set.
CHAPTER 2. MEASUREMENT OF PARAMETERS FOR EMPIRICAL MODELING OF VIBROTHERMOGRAPHIC HEATING

Modified from a paper to be submitted to NDT&E International

Tyler Lesthaeghe, Jyani Vaddi, Stephen Holland, William Meeker, Ashraf Bastawros

2.1 Abstract

Vibrothermography is a nondestructive testing technique that uses vibration-induced heating to locate cracks inside parts. Industrial application of vibrothermography has typically been limited due to, among other things, a lack of complete understanding of the factors influencing vibrothermographic crack heating. This paper outlines the details of an empirical model of vibrothermographic crack heating incorporated as a component of a complete model of the vibrothermography process, alongside FEM models of vibration and heat flow. The empirical model considers heating as a product of factors considering vibrational energy, crack relative mobility, and crack closure. A series of measurements inform the empirical model. Details are provided, including the details of a vibrothermography-based method for determining crack closure state, and results are summarized. Subsequent statistical modeling results, briefly summarized, show reasonable agreement with expected values.
2.2 Introduction

Vibrothermography is a promising nondestructive testing technique for locating cracks utilizing vibration-induced heating. However, industrial application of this technique has been limited due to concerns related to repeatability – more specifically, under the same vibration conditions, crack heating can vary quite significantly between cracks.

To improve our understanding, an effort is underway to develop a forward model of the vibrothermography process. We are breaking the problem down into its three physical components, modeled separately and then connected into a modeling tool called VibroSim[7], operating on top of COMSOL Multiphysics [11]. These three components, as seen in Figure 2.1, mirror the real world physical phenomena behind vibrothermography: 1) vibration from a transducer excites resonant frequencies inside a part, 2) vibrational energy is converted into heat at the location of a crack, and 3) heat flows to the surface of the part and is imaged utilizing an infrared (IR) camera. The vibration and heat flow problems are suited to the use of a finite element model and are solved using the COMSOL engine. However, the vibration problem does present challenges in accurately modeling mounting and vibration damping, the details of which can be seen in [12].
The crack heating problem is less suited to be solved with a finite element model. While an explicit model may be possible, it would likely contain too many free parameters to provide any predictive capacity, especially considering the amount of crack to crack variability often seen. This is due to the physics behind vibrothermographic crack heating not yet being well understood, though there is some work suggesting possible crack heating mechanisms [6; 7].

As a result, an empirical model is much better suited to describing crack heating. The empirical model represents thermal power per unit area as a product of factors that consider the effect of vibrational energy, crack mobility, and crack closure. A series of experiments were performed on a set of Inconel 718 and Titanium-6Al-4V rectangular bar specimens with fatigue cracks to evaluate the effects of these parameters.

### 2.3 Model Development

The empirical model is given as

\[ P = vmc \]  

(2.1)

where \( P \) is thermal power per unit area, \( v \) is a factor describing the effect of vibration, \( m \) is a factor describing the relative mobility of the crack, and \( c \) is a factor describing crack closure. Describing these factors as multiplicative naturally makes sense, as any individual parameter could effectively zero out the influence of the other parameters and result in no crack heating. We make the assumption that the three parameters are physically independent of each other and therefore a simple product can represent the combined effect. The assumption of independence is critical to keeping the model simple.

Figure 2.2 shows representative experimental data, and will be used to explain the individual portions of the empirical model. The plot is a summary of many individual vibrothermographic measurements performed at a variety of bending stresses, plotted on
the y axis in Figure 2.2. Heating is discretized into approximately 30 to 40 bins along the crack length, plotted on the x axis. Details of how this data is collected will be presented later.

2.3.1 Vibration

We chose to model vibration utilizing a power law

\[ v = e^{V_0} \left( \frac{\epsilon_{md}}{50 \times 10^{-6}} \right)^{V_1} f \]  

(2.2)

where \( V_0 \) and \( V_1 \) are free model parameters, \( \epsilon_{md} \) is the magnitude of the dynamic engineering strain at the crack, and \( f \) is the excitation frequency.

Increasing vibrational excitation amplitude, as seen from left to right in Figure 2.2, results in an increase in heating. It is expected that heating will have between a linear and quadratic dependence on vibrational strain [13], and thus \( V_1 \) should be between 1 and 2. The currently proposed underlying physical mechanism behind crack heating, adhesion hysteresis and/or frictional heating, also supports this [7].
Dynamic engineering strain, $\epsilon_{md}$, is defined as the vector magnitude of the strain across the crack at the center location in a hypothetical identical specimen without a crack. In simulation, $\epsilon_{md}$ is determined directly. In experiment, it is determined by recording the motion of the vibrating sample with a laser vibrometer at a particular point. Simulation provides the resonance mode shape of the specimen, which determines the ratio between motion at the vibrometer point and the strain tensor at the hypothetical crack location. We can then take the $\ell^2$ norm of the product of the strain tensor and a unit vector normal to the crack face. Proportionality with excitation frequency, $f$, is based on theory and previous experimental results [14].

### 2.3.2 Relative Mobility

Relative mobility represents a constraining effect due to pressure from nearby crack tips limiting the motion of the crack faces; a factor designed to reconcile the fact that very short cracks ($< 1$ mm) tend to heat less [15]. However, past a certain length (3-4 mm), the amplitude of crack heating tends to stay roughly the same. Additionally, as can be seen in Figure 2.2, heating tends not to occur near the crack tips in general. This suggests a sigmoidal logistic form

$$m(x) = \frac{1}{1 + \exp \left(-m_1 \left(l_{tip}(x) - l_0 \right)\right)}$$

(2.3)

where $m_1$ and $l_0$ represent the free model parameters describing the reciprocal of the transition width and transition position, respectively, and $l_{tip}$ is the distance between the position of interest, $x$, and the nearest crack tip. Figure 2.3 shows the form of this function and these parameters.

An alternative explanation is that mobility may be the result of an extrinsic effect, such as crack closure. However, since crack heating does not occur near the tips, it is difficult for us to define a closure state at these positions. Therefore, the relative mobility parameter still provides a meaningful parameter to handle both heating near the crack tips and very short cracks.
2.3.3 Crack Closure

Crack closure describes a state in which crack faces are in contact and under load in the absence of external load [16]. Significant compressive closure stresses can exist along the length of a crack and can actually approach the yield strength near the crack tips [17]. The primary cause of this residual stress is due to material being displaced and permanently stretched in a plastic zone at the crack tips formed during fatigue crack growth; though several other mechanisms can contribute to closure, including roughness effects and oxide related factors [17]. The effect of crack closure is believed to be one of the most significant factors in controlling the location and intensity of vibrothermographic crack heating [18]. Intuitively, heating would not be expected at a location where a crack is held shut so tightly that the amplitude of the applied vibration would be unable to overcome the closure stresses. Nor would heating be expected at a location where the crack faces are so far separated that they are unable to contact during excitation.
Rather, heating occurs at the location where closure stress is roughly 0 [18].

This work employs and expands upon the methods of [18]. As previously mentioned, Figure 2.2 shows heating as a function of position along the crack and applied external bending stress. This plot shows that bands of heating occur and shift as external bending stresses are applied to modify the closure state.

We have modeled this behavior with

\[
c(x) = \frac{1}{4w_h} \exp \left( -\frac{\sigma_c(x) - \sigma_{c0}(x)}{2w_h} \right)
\]

(2.4)

where \( \sigma_c \) is the closure stress acting to hold the crack closed at any particular location along the crack, \( \sigma_{c0} \) is the closure stress state at the crack that results in maximum heating at the point \( x \), and \( w_h \) quantifies the range of stress levels over which the crack at any particular location will heat. Since the intrinsic closure state as defined when the crack is unloaded, \( \sigma^{\mu}_c \), is directly proportional to the closure state defined in terms of external bending stress, \( \sigma_{ext} \), and since Equation 2.4 has been normalized to integrate to 1, we can perform model fitting with \( \sigma_c \) and \( \sigma_{c0} \) expressed in terms of external bending stresses for simplicity. Figure 2.2 and all subsequent figures and equations will be in terms of external bending stress.

### 2.3.4 Combined Empirical Model

The combined empirical model takes the form

\[
P(\epsilon_{md}, f, l_{tip}, x, \sigma_{ext}, \sigma_{ext0}, w_h) = e^{V_0 \left( \frac{\epsilon_{md}}{100 \times 10^{-6}} \right)^{V_1}} f \\
\times \frac{1}{1 + \exp \left( -m_1 (l_{tip}(x) - l_0) \right)} \\
\times \frac{1}{4w_h} \exp \left( -\frac{\sigma_{ext} - \sigma_{ext0}(x)}{2w_h} \right)
\]

(2.5)

which requires the fitting of the free model parameters \( V_0, V_1, m_1, \) and \( l_0 \) given the inputs of \( \epsilon_{md}, f, l_{tip}, x, \sigma_{ext}, \sigma_{ext0} \) and \( w_h \). Here, we specify that \( \sigma_{ext0} \) and \( w_h \) are inputs, determined during data collection and post-processing as described below. However,
additional work is ongoing to obtain a better predictive capacity over these parameters and better enable the use of this model in real world components [7].

2.4 Methods

2.4.1 Experimental Test Specimens

A quantity of 16 rectangular bar specimens with approximate dimensions 10 in x 1 x 0.5 in and made out of Inconel 718 and Titanium-6Al-4V were used. Specimen length varied slightly between the two materials to have better control with respect to vibration modeling. Fatigue cracks were grown to approximately 4 mm on the majority of specimens with an R-ratio of 0.1 and loading both at 70% and 85% of yield. Table 2.1 shows the specific dimensions, crack, and fatigue parameters for each specimen. EDM starter notches with an approximate 0.8 mm width were machined off and the specimen surface was subsequently polished to a 1 micron finish. Figure 2.4 shows the position of the crack with respect to the specimen geometry, located at the center of the largest face of the bar.

2.4.2 Bending Apparatus

A bending apparatus capable of supporting experimental test specimens and all of the necessary equipment to perform vibrothermography measurements was custom designed and built utilizing a heavily modified shop press. Figure 2.5 shows a rendering of the setup with an experiment test specimen under load. Test specimens are mounted in a 4-point bending configuration, so as to open and close the crack, changing its closure state.
Table 2.1 Details of Test Specimen Set

<table>
<thead>
<tr>
<th>Set</th>
<th>Specimen</th>
<th>Material</th>
<th>Specimen Geometry (mm)</th>
<th>Crack Parameters (mm)</th>
<th>Fatigue Process</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td>Length</td>
<td>Width</td>
<td>Thickness</td>
</tr>
<tr>
<td>Baseline Specimens</td>
<td>C14-UTCA-002X</td>
<td>Ti 6-4</td>
<td>246.28</td>
<td>26.2</td>
<td>12.52</td>
</tr>
<tr>
<td></td>
<td>C14-UTCA-005K</td>
<td>Ti 6-4</td>
<td>246.25</td>
<td>26.24</td>
<td>12.54</td>
</tr>
<tr>
<td></td>
<td>C14-UTCA-008F</td>
<td>Ti 6-4</td>
<td>246.48</td>
<td>26.24</td>
<td>12.19</td>
</tr>
<tr>
<td></td>
<td>C14-UTCA-011G</td>
<td>Ti 6-4</td>
<td>246.25</td>
<td>26.23</td>
<td>12.32</td>
</tr>
<tr>
<td></td>
<td>C14-UTCB-004F</td>
<td>In 718</td>
<td>276.62</td>
<td>26.12</td>
<td>12.80</td>
</tr>
<tr>
<td></td>
<td>C14-UTCB-005A</td>
<td>In 718</td>
<td>275.97</td>
<td>26.18</td>
<td>12.79</td>
</tr>
<tr>
<td></td>
<td>C14-UTCB-010A</td>
<td>In 718</td>
<td>277.57</td>
<td>26.16</td>
<td>12.73</td>
</tr>
<tr>
<td></td>
<td>C14-UTCA-020E</td>
<td>In 718</td>
<td>276.44</td>
<td>26.24</td>
<td>12.85</td>
</tr>
<tr>
<td>85% Yield</td>
<td>C14-UTCA-007C</td>
<td>Ti 6-4</td>
<td>246.25</td>
<td>26.26</td>
<td>12.56</td>
</tr>
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<td></td>
<td>C14-UTCA-013E</td>
<td>Ti 6-4</td>
<td>246.46</td>
<td>26.16</td>
<td>12.58</td>
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<td></td>
<td>C14-UTCB-003P</td>
<td>In 718</td>
<td>276.35</td>
<td>26.12</td>
<td>12.84</td>
</tr>
<tr>
<td></td>
<td>C14-UTCB-008G</td>
<td>In 718</td>
<td>275.40</td>
<td>26.18</td>
<td>12.82</td>
</tr>
<tr>
<td>Short Crack</td>
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<td>Ti 6-4</td>
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<td>26.30</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C14-UTCA-009A</td>
<td>Ti 6-4</td>
<td>246.22</td>
<td>26.24</td>
<td>12.38</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C14-UTCA-010K</td>
<td>Ti 6-4</td>
<td>246.34</td>
<td>26.20</td>
<td>12.45</td>
</tr>
</tbody>
</table>
2.4.3 Vibrothermography Measurement Process

The thermal measurement process utilizes a broadband PZT-based transducer cycled over the 1-60 kHz frequency range for 1 second. This sweep measurement is performed with a laser vibrometer pointed at a known location on the specimen. Resonant frequencies are identified and the actual vibrothermography measurement is performed utilizing a constant frequency burst excitation at the resonant frequency determined from the broadband sweep. The measurement of specimen motion, combined with a known resonance mode behavior from FEM simulation, enables us to quantitatively determine the strain at the crack as a function of time and ensures that the maximum strain possible is occurring at the location of the crack.

Figure 2.4 shows a rendering of the displacement field and strain for the excited resonant frequency with respect to the geometry and crack position. For the purposes of this set of experiments, the 9th mode flexural resonance was targeted after a preliminary set of experiments found this mode was well separated from other resonant modes, mini-
Figure 2.5 Rendering of Modified Shop Press for Vibrothermographic Crack Closure Measurement
mizing the risk of interference, and was also ideal for our equipment setup and specimen geometry.

A thermal camera with a microscopic lens is mounted to a motion stage above the cross-head of the press and captures thermal images of heating through a hole in the cross-head plate, as seen in Figure 2.5. Thermal imaging is accomplished by covering the region around the crack with a black paint made from a laser toner, gum arabic, and water mixture.

2.4.4 Optical Measurement Process

In addition to vibrothermographic measurements, a series of optical measurements are also performed on each specimen. These optical measurements provide registration between all images. This enables us to know explicitly where the crack is located within thermal images, allowing the calculation of $l_{tip}$.

Optical measurements use a visible light camera with a microscope objective mounted to the motion stages to capture high resolution stitched optical images.

2.4.5 Post Processing

Post processing can be broken down into several steps:

1. Optical images are stitched and aligned.

2. Thermal images aligned with respect to each other and the optical images.

3. The physical crack location is identified.

4. Necessary parameters, $\epsilon_{md}$, $\sigma_{ext}$, $x$, $l_{tip}$, and $f$, are extracted and/or calculated.

5. Heating is discretized and thermal power is calculated.

6. Crack closure parameters $\sigma_{ext0}$ and $w_h$ are determined.
7. Data is output and saved in a convenient format for statistical analysis. Items 1-4 and 7 are completed utilizing automated processes where possible.

Item 5 is completed by discretizing heating into approximately 20-30 bins along the crack to provide a more manageable data set for statistical analysis and empirical model fitting. Heating values within each bin are determined by averaging in the direction along the crack length and then performing a curve fit in the perpendicular direction to the Green’s function solution for two dimensional heat conduction, given by

\[
\bar{T} \left( \bar{t} \right) = - \text{Ei} \left( - \frac{\bar{R}^2}{\bar{t}} \right)
\]  

(2.6)

where \( \text{Ei} \) is the exponential integral function, \( \bar{T} \) is normalized temperature, \( \bar{R} \) is the normalized source distance, and \( \bar{t} \) is normalized time [8]. This process results in a significant reduction in noise by averaging over a large number of pixels. Thermal power is determined utilizing an algorithm discussed in [19]. This algorithm models the crack as a series of sources drawn as concentric annuli and determines thermal power by linear inversion. The heat flow model uses the same concentric annuli source distribution, enabling the empirical model to act as an input to the heat flow model.

Crack closure parameters, item 6 above, are determined by a process seen in Figure 2.6. Heat intensity is plotted as a function of applied external bending stress \( \sigma_{ext} \) and position along the crack \( x \) for each set of measurements on a particular crack.

It was originally intended to determine closure parameters using an automated curve fit; however, automated curve fits tend to have a hard time dealing with situations where the physical behavior does not match the oversimplified model. In these cases, \( \sigma_{ext0} \) is usually shifted away from the proper location, as seen in the left pane of Figure 2.6.

Instead, an interactive process was used. The user identifies the location of maximum heating, \( \sigma_{ext0} \), along the crack by selecting points inside this plot. The user then
Figure 2.6 Crack Closure State Determination

determines the width of the heating band, $w_h$, by selecting the appropriate point on the plot, resulting in a line being drawn in from the previously defined $\sigma_{ext0}$.

2.5 Testing and Results

A total of 19 unique cracks were tested using this process (several specimens contained two cracks). Tests were generally performed at bending stresses in 10 MPa increments randomly ordered between 20 MPa and 240 MPa. Three excitation voltages were also used to examine vibration dependence on heating. Several cracks were also tested twice to perform an examination of repeatability.

Figure 2.7 shows heating as a function of position and external bending stress for several representative cracks. These plots are interpreted in the same way as described for Figure 2.2. Figure 2.8 shows a plot of crack closure state as a function of normalized position for the tested cracks. This figure indicates a dependence of material as a significant factor in closure state.
The processed data, along with values of $\sigma_{ext0}$ and $w_h$, were provided to a statistical research team to fit the remaining model parameters. The details of this process can be seen in [7]. Values for $V_0$ and $V_1$ have been determined for each individual specimen and appear consistent with expected results. A summary of these values can be seen in Table 2.2.

### 2.6 Conclusions

When coupled with models of the vibration process and heat flow process, this work provides a predictive forward model of the vibrothermography process. The empirical model presented considers the influences of vibration, crack mobility and crack closure. This work further demonstrates the viability of performing quantitative crack closure measurement utilizing vibrothermography. Finally, the nature of the presented measurement process, combined with the quantity and quality of data collected, open the door to probing other controlling factors of vibrothermography.
Figure 2.8 Crack Closure Stress, $\sigma_{ext0}$, as a Function of Normalized Position for Tested Cracks

Table 2.2 Estimates of $V_0$ and $V_1$ from Statistical Analysis

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Crack</th>
<th>$\hat{V}_0$</th>
<th>$\hat{V}_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C14-UTCA-004G B</td>
<td>1.53</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>C14-UTCA-005K A</td>
<td>2.51</td>
<td>2.07</td>
<td></td>
</tr>
<tr>
<td>C14-UTCA-007C A</td>
<td>2.82</td>
<td>1.29</td>
<td></td>
</tr>
<tr>
<td>C14-UTCA-008F A</td>
<td>2.02</td>
<td>1.46</td>
<td></td>
</tr>
<tr>
<td>C14-UTCA-009A B</td>
<td>3.73</td>
<td>1.48</td>
<td></td>
</tr>
<tr>
<td>C14-UTCA-010K B</td>
<td>2.05</td>
<td>1.41</td>
<td></td>
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<tr>
<td>C14-UTCA-011G A</td>
<td>2.52</td>
<td>1.00</td>
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<tr>
<td>C14-UTCA-013E A</td>
<td>2.83</td>
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<td></td>
</tr>
<tr>
<td>C14-UTCB-004F A</td>
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<td></td>
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<tr>
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<td>2.58</td>
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<td></td>
</tr>
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<td>3.02</td>
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<td>C14-UTCB-020E A</td>
<td>3.40</td>
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</tbody>
</table>
This material is based on work supported by the Air Force Research Laboratory under Contract #FA8650-10-D-5210, Task Order #023, and performed at Iowa State University.
CHAPTER 3. LUBRICANT INCREASES VIBROTERMLOGRAPHIC CRACK HEATING

Modified from a paper to be submitted to the Review of Progress in Quantitative Nondestructive Evaluation

Tyler Lesthaeghe, Stephen Holland, Ashraf Bastawros

3.1 Abstract

Fatigue cracks in several specimens were intentionally contaminated with a lubricating oil in an attempt to probe the underlying physical mechanisms behind vibrothermographic crack heating. It was observed that crack heating will consistently and repeatably increase with the presence of oil; however, increasing excitation amplitude appears to reduce the effect, and perhaps may even result in a net decrease in heating under high excitation amplitudes. We hypothesize these effects are being caused by viscous heating of the oil, with the inverse amplitude dependence being explained by the effect of resistance from the compression of the oil at higher amplitudes reducing the forces driving vibrothermographic crack heating. Additional work is needed to further understand this behavior.

3.2 Observation

Lubricating oil was introduced into a fatigue crack as a part of a process to better understand the underlying physical mechanisms behind vibrothermographic crack heating. Current knowledge suggests that friction or adhesion hysteresis are the likely underlying mechanisms [7].
Our belief was that the introduction of lubricating oil would interfere with these mechanisms and reduce the level of heat generated. However, the end result was a clear and consistently repeatable increase in heating – with an inverse dependence on excitation amplitude.

### 3.3 Methods

As a part of a broader modeling effort, our group has custom built an apparatus for probing the closure state of a crack. This apparatus enables us to peel the crack open and ensure full
penetration of oil in the crack. Figure 3.1 shows a diagram of the experiment setup.

The basic testing process is outlined as follows:

1. Specimen cleaning is performed to ensure crack is clear of contaminants.

2. Control measurements are performed.

3. Oil is introduced into the crack.

4. Measurements are repeated with oil in the crack.

5. Specimen cleaning is performed again to remove oil from the crack.

6. Control measurement is repeated.

Several specimens with 4 mm long fatigue cracks were cleaned utilizing standard ultrasonic cleaning procedures with acetone [20]. Each specimen was painted with a black paint to facilitate thermal imaging. The specimen was then loaded in the bending apparatus in a four-point bending configuration such that a static tensile bending stress of 60 MPa was peeling the crack open. After this point, the bending stress applied was never lowered below 60 MPa.

Baseline vibrothermographic measurements were performed at static bending stresses of 70 MPa, 110 MPa, and 180 MPa, monotonically. These bending values were chosen to provide a range of varied crack closure states with reasonably different heating without the need to perform measurements for all closure states. Vibration was introduced using a PZT actuator with a tone burst designed to excite the 9th mode flexural resonance such that the crack experiences mode I opening and closing motion.

After the three baseline measurements were performed at varying closure states, the sample was then cleaned by wiping across the surface with a cloth. This was first done using water to remove the water-soluble paint, and then with acetone to clean the surface. It should be noted that this is not the normal cleaning procedure; however, in this experiment, we were also seeking a high level of repeatability between measurements. Therefore, we did not wish to unmount the specimen and introduce the variability associated with changes in mounting.

To introduce oil into the crack, the specimen was loaded to 240 MPa. A custom designed 3D-printed fixture, seen in Figure 3.2, was mounted to the specimen and connected to a vacuum
pump. Early tests with utilizing a vacuum to increase the odds of a fluid being introduced into the crack resulted in issues with the fluid being pulled back into the vacuum pump rather than into the crack. The fixture allows us to pull a vacuum and then introduce oil by opening a valve and flooding the inside of the chamber. While some oil was still being pulled back into the vacuum pump, the quantity was significantly reduced and a pool of oil around the crack was left behind afterwards. A napthenic base lubricating oil was chosen for this process.

Following the introduction of oil, the bending stress was lowered back down to 60 MPa. A non-absorptive cloth was used to wipe the area around the crack to remove excess oil and allow the paint mixture to stick. The sample was repainted and retested again at 70 MPa, 110 MPa, and 180 MPa. As an additional evaluation of repeatability and our cleaning process, the specimen was then unloaded, cleaned using the standard cleaning procedure, and then retested again at 70 MPa, 110 MPa, and 180 MPa. This process was repeated on several different specimens with one specimen being tested at several additional bending stresses.

### 3.4 Results

The results from this process were unexpected – a clear increase in heating for an oil contaminated crack. Figure 3.3 shows that the introduction of oil results in a definite increase in heating, in some cases more than two times the baseline heating. This plot also shows that as heating amplitude decreases, the effect remains, but becomes less significant as we cross below the noise threshold. Finally, it can be noted that our cleaning procedure appears to have successfully removed the oil from the crack, as heating levels return to normal after cleaning.

In an attempt to further quantify the effect, a follow up set of measurements were performed for one sample at all bending stress states between 20 MPa and 240 MPa in 10 MPa increments in random order. Excitation amplitude was also varied. The details of this measurement process are described in more detail in [21]. Figure 3.4 shows a summary of this collected data. The top row of figures display pre-oil heating and the bottom row display post-oil heating from lower excitation amplitude to higher amplitude from left to right. Each row within each image represents the discretization of one individual measurement along the length of the crack.
performed at a range of external bending stresses.

Figure 3.5 shows a scatter plot of heating intensity after oil introduction versus heating intensity before oil introduction for each individual data point summarized in Figure 3.4. Pixels within the clear banded heating region in Figure 3.4 are displayed in green in Figure 3.5. Points below and outside the banded heating region are displayed in red and points inside and above the banded heating region are displayed in blue. See [21] for more details of how this banded heating region is defined.

Figure 3.5 shows that at low excitation amplitudes, it appears that all points, with some amount of noise and error, produce higher amounts of heat after the introduction of oil. The amount of increase in heating decreases with increasing excitation amplitude, to the point that at the highest excitation amplitude tested, heating appears to be about normal, if not slightly decreased.
Figure 3.4  Heating as a Function of Position, Applied Bending Stress, and Excitation Amplitude Before and After Oil Introduction
Figure 3.5  Scatter Plot Quantifying Heating Increase as a Function of Position, Applied Bending Stress, and Excitation Amplitude Before and After Oil Introduction
3.5 Explanations

At this point, we are unsure of the physical mechanism behind this behavior. We hypothesize the potential for viscous heating of the oil. The previously noted increase in heating at all points along the crack would seem to support this idea. We additionally hypothesize that the decrease in this effect with increasing amplitude could be explained by the resisting force along the crack faces due to the compression of the oil is approaching the order of magnitude of crack motion that provides vibrothermographic crack heating, thus resulting in a decrease of vibrothermographic crack heating without necessarily producing an increase in viscous heating needed to offset the loss. More work is needed to better understand this behavior.

This material is based on work supported by the Air Force Research Laboratory under Contract #FA8650-10-D-5210, Task Order #023, and performed at Iowa State University.
CHAPTER 4. EXTENSIBLE PLATFORM FOR THE VIEWING OF LARGE LABORATORY DATA SETS

Modified from a paper to be submitted to the *Review of Progress in Quantitative Nondestructive Evaluation*

Tyler Lesthaeghe and Stephen Holland

4.1 Abstract

This work discusses the development of Databrowse, an extensible web-based platform for the viewing and transformation of large laboratory data sets. Utilizes eXtensible Markup Language (XML) representations of data, this tool is able to leverage the power of high performance open source engines to parse, query, and transform large data sets extremely quickly. The basics of XML and the language used to define transformations (XSLT or eXtensible Stylesheet Language Template) are described. Our experiences with using this tool with real data sets are also detailed.

4.2 Introduction

Nondestructive evaluation (NDE) techniques are capable of generating considerable amounts of data in very short periods of time. However, many industrial inspections today produce a simple pass/fail response as a result of a testing process. Recorded raw data is often viewed as useless, or potentially even a liability, unless we have ways to extract useful information. Ultimately, the problem of finding a needle in a haystack is particularly challenging, especially if you do not know what you are looking for.
Even in research scenarios where we desire to collect large quantities of data to examine specific items, handling large quantities of data can still be a challenge. As a part of a recent modeling effort related to development of a forward model for vibrothermography, a nondestructive testing technique that utilizes vibration-induced heating to located cracks in materials, the need became apparent for better tools and data management practices. It was known at the beginning of the work that a considerable amount of data was to be generated. In the end, a final data table containing almost 25,000 entries was generated, along with over 0.5 TB of raw data.

The authors sought to develop a tool that would help in the short term for dealing with the latter problem, while serving as a spring board to further work toward dealing with the former problem. The end result was a tool called Databrowse.

Databrowse is an extensible web-based platform for data viewing, manipulation, and management. At the most basic level, Databrowse is a file browser; however, simple plugins enable Databrowse to represent data of a variety of formats in a consistent way, enabling rapid viewing and transformation of those views to narrow in on features of interest. The plugin architecture enables Databrowse to be adapted to support any data format in which knowledge of the data format is available. Data from multiple sources or formats can be pulled together into combined representations and then further transformed as desired. Furthermore, all of these transformations are performed in real time.

4.3 Implementation

4.3.1 XML

Databrowse represents data as XML [22]. XML (eXtensible Markup Language) is a standard that allows text data to be hierarchically structured utilizing arbitrarily defined tags. Special engines can then be used to parse and manipulate such structured data. Figure 4.1 shows an example of a simple data set being structured and stored in an XML format. The first line of the sample XML file shows an experiment tag, and the last line shows that tag being closed. Everything contained between the opening and closing tags can be described as
Figure 4.1 Sample XML Data

children. In this context, our measurements are children of the experiment. Thus, a hierarchical data structure can be developed. Subsequently, we have represented all of the individual parameters for each measurement as children of that measurement.

We can take it a step further and indicate that one of these parameters could have multiple values, as seen with the voltage data. This is one major advantage of this type of data structure, as our spreadsheet style data table does not necessarily make representing this type of data structure easy. We have made it work here with a comma list of values in our data table; however, this does not work so easily with more complicated data.

Furthermore, XML tends to work very nicely as a way of representing most data, since many frequently used data formats internally represent data in a natural hierarchical structure, often as a convenient way of dealing with the issue just described. Therefore, conversion to XML, if even required, is generally very straightforward. Once represented as XML, Databrowse is able to leverage the power and speed of the open source XML engine libxml2 [23]. The result is being able to parse and transform considerable amounts of data in seconds.

It is important to note that raw binary waveforms are not intended to be represented as XML; however, pieces of them might be. More typically though, a plugin would utilize an
interface provided by Databrowse that enables the creation of images of such data. Such an image can be generated in real time and served to the web browser by Databrowse. This would not be limited to images. Any format that could be displayed in a web browser could be used, such as videos, animations, or any format that can use a web browser plugin to display.

4.3.2 XSLT

Databrowse utilizes XSLT [24] to transform data. XSLT (eXtensible Stylesheet Language Template) provides an interface by which the user can define a set of transformations to be applied to XML data. In other words, XML data and XSLT templates designed to act on that data are provided to the XSLT engine and the engine will output a new set of XML data based on the transformation provided. This behavior can be seen in Figure 4.2, where our sample data from Figure 4.1 has been transformed using an XSLT template.

Databrowse, being a web based platform, wants to build web pages utilizing the data being provided. HTML, the language with which web pages are built, is a type of XML. As a result, our XSLT transform is able to take our data file and build a web page dynamically in real time. Databrowse then handles the process of serving that web page to a user in their web browser.

4.3.3 Databrowse Plugins

Databrowse plugins are responsible for providing the following: 1) registering the file types with which they should be able to operate on, 2) providing an XML representation of the file, and 3) providing an XSLT transform that converts the XML representation to the desired HTML view that is displayed in the web browser. Plugins are also able to provide additional features that can be triggered or accessed from the web view. Such features might include the automatic generation of animations, data conversions, or running of processing scripts.

Since every file can be represented as XML, Databrowse provides an interface for recursively obtaining an XML representation of entire directories and sub-directories. Thus, a single representation of multiple files can be obtained. In addition to providing a set of plugins for some common file types, Databrowse includes some plugins designed to provide a simple interface for
Figure 4.2 Sample XML Data being Transformed with XSLT
building such combined representations. XSLT transformation stylesheets can also be provided on a per-directory basis if additional control is needed for specific use cases.

### 4.4 Experiences

In order to really be able to use the power of Databrowse to its fullest, some changes needed to be made to the data collection process. In addition to Databrowse, we also developed a tool called Datacollect to aid in automating and enhancing the data collection process. This tool saves XML experiment logs that record all of the parameters of a particular measurement and references to the raw binary data files. These experiment logs and the nature of how they are recorded are particularly critical to being able to utilize the viewing and transformation capabilities of Databrowse. As an aside, they also provide a very accurate record of work performed and reduce the chance of human error while performing data processing.

Even without the parameters of an experiment being represented in a parsable digital format, Databrowse provides a simple mechanism for managing tools that perform processing and analysis of data. Instead of having lots of copies of the same processing script with every new data set, a Databrowse plugin designed to work on a particular type of data can be built to perform these functions, along with providing quick access to visualization and reporting tools.

Additionally, Databrowse became an excellent platform for building management tools. During the course of this work, a specimen database and a transducer database were developed. Information pertaining to a particular specimen or transducer was contained within an XML file. XSLT transforms were used in conjunction with Databrowse’s ability to recursively build a complete representation of an entire folder to produce a web based tool for managing information about specimens and transducers. Databrowse’s Python bindings can then be used to write scripts that query this information, enabling quick access to information about these items. Undoubtedly, countless other possibilities exist to utilize this infrastructure for other similar purposes, enabling rapid deployment of what would have otherwise been a fairly complicated task.
The true power of this tool became particularly apparent as we were concluding data collection and processing as a part of the vibrothermography project previously mentioned. Using Datacollect, we were able to rapidly record a considerable amount of data. In fact, 1107 individual vibrothermography measurements were performed over the course of a month, approximately half of these measurements occurring over the course of a 72 hour period. After post processing, all of this data needed to be exported to a CSV format to be shared with research partners.

Utilizing the simple interface mentioned for building combined representations of data mentioned previously, we were able to, within a matter of minutes, write the template needed to pull all of this data in from multiple sources, pull out only the features of interest, produce calculated values based on data contained within this set, and export a CSV file containing the final results. This CSV file, produced in a little more than a second, contained almost 25,000 rows of data and 20 columns, about half of which were manipulated or dynamically generated in some way.

4.5 Future Work

Moving forward, we are looking to continue improvements and enhancements to the system. Many opportunities are available to utilize open source tools to enable interactive browsing of raw waveform data, and we look to implement a mechanism to make such features available to plugins easily. Additionally, we look to continue to expand the available plugins to support a wide variety of data formats. Specifically, DICONDE and HDF5 data formats are on the list of formats to be implemented.

The longer term goal will be to evaluate how we can leverage the capabilities provided by Databrowse to solve the big data problems associated with querying NDE data. Returning to the needle in a haystack analogy, Databrowse provides the means with which to generate a representation the haystack. However, a considerable amount of additional work will be needed to develop the tools for finding the needle.
This material is based on work supported by the Air Force Research Laboratory under Contract #FA8650-10-D-5210, Task Order #023, and performed at Iowa State University.
CHAPTER 5. GENERAL CONCLUSIONS

The work presented in this thesis represents an important portion of a much larger research effort into the forward modeling of the vibrothermography process, a model aiming to provide the predictive capacity required for model assisted POD for vibrothermography. Such a step is critical to further wide spread use and acceptance of vibrothermography in industrial inspection.

This thesis presents an empirical model for vibrothermographic crack heating. A data collection process that enables the rapid acquisition of significant amounts of relevant high quality data for the purposes of fitting model parameters has been outlined. The process also further builds upon the technique suggested by Renshaw, et al. [18] for high quality crack closure measurement. Additionally, the equipment setup and data collection process opens the door to further analysis of additional parameters not yet defined, particularly as our understanding of the underlying physics continues to develop.

This work also presents one such effort into better understanding of the underlying physical mechanisms of vibrothermographic crack heating. Lubricating oil was introduced into a crack with the expectation that heating would decrease; however, we have shown that, at least under the proper excitation conditions, heating actually increases. Furthermore, it appears that this effect decreases with increasing excitation amplitude. We hypothesize a potential explanation; however, additional work is still needed in this area.

Finally, a tool is presented that enables the rapid viewing and transformation of large laboratory data sets, such as the large data set collected as a part of the empirical modeling process. Originally motivated in the short term to meet the needs for managing data in this project, the tool lays down a framework for future work in exploring big data problems in NDE and development of tools for querying and answering high level questions based on large
laboratory data sets.

Moving forward, additional work will be performed to continue improving the empirical model developed during this work, exploring additional relevant parameters, improving measurement processes, developing improved tools and methods for closure state determination and prediction, and further validation. The oil testing results will be further validated and additional experiments and work may be performed to validate the hypothesis presented. Additional work along these lines will continue to better understand the physics behind crack heating. Finally, tools and processes will continue to be developed for working with and handling large laboratory data sets.
APPENDIX. COMPLETE EXPERIMENTAL RESULTS

This appendix presents a complete record of experimental data results obtained during the empirical modeling effort described in Chapter 2. For each test on each crack, two side-by-side plots are displayed. The left pane displays discretized heating as a function of applied external bending stress and position along the crack utilizing the methods discussed in Chapter 2. Individual data points were determined by discretizing the raw thermal images into 176 micron wide bins along the crack, averaging pixels along the length of the crack and performing a fit using Equation 2.6 in the direction perpendicular to the crack. The right pane in each image displays thermal power as calculated utilizing the methods discussed in [7; 19].

Table 2.1 provides a reference of specimens, materials, crack and fatigue parameters for all of the data presented in Figures A.1-A.53.
Baseline Specimen Set

Figure A.1  Processed Experiment Results from Baseline Testing for C14-UTCA-002X
Tested at 1.5 V

Figure A.2  Processed Experiment Results from Baseline Testing for C14-UTCA-008F
Tested at 1.5 V
Figure A.3  Processed Experiment Results from Baseline Testing for C14-UTCA-011G
Tested at 1.5 V

Figure A.4  Processed Experiment Results from Baseline Testing for C14-UTCB-004F
Tested at 1.5 V
Figure A.5  Processed Experiment Results from Baseline Testing for C14-UTCB-005A
Tested at 1.5 V

Figure A.6  Processed Experiment Results from Baseline Testing for C14-UTCB-007J
Tested at 1.5 V
Figure A.7  Processed Experiment Results from Baseline Testing for C14-UTCB-010A
Tested at 1.5 V

Figure A.8  Processed Experiment Results from Baseline Testing for C14-UTCB-020E
Tested at 1.5 V
85% Yield Specimen Set

Figure A.9 Processed Experiment Results for C14-UTCA-007C Tested at 1.5 V

Figure A.10 Processed Experiment Results for C14-UTCA-007C Tested at 1.0 V
Figure A.11 Processed Experiment Results for C14-UTCA-007C Tested at 0.75 V

Figure A.12 Processed Experiment Results for C14-UTCA-013E Tested at 1.5 V
Figure A.13  Processed Experiment Results for C14-UTCA-013E Tested at 1.0 V

Figure A.14  Processed Experiment Results for C14-UTCA-013E Tested at 0.5 V
Figure A.15  Processed Experiment Results for C14-UTCB-003P Tested at 1.5 V

Figure A.16  Processed Experiment Results for C14-UTCB-003P Tested at 1.0 V
Figure A.17  Processed Experiment Results for C14-UTCB-003P Tested at 0.5 V

Figure A.18  Processed Experiment Results for C14-UTCB-008G Tested at 1.5 V
Figure A.19  Processed Experiment Results for C14-UTCB-008G Tested at 1.0 V

Figure A.20  Processed Experiment Results for C14-UTCB-008G Tested at 0.5 V
Short Crack Set

Figure A.21 Processed Experiment Results for C14-UTCA-004G Crack A Tested at 1.5 V

Figure A.22 Processed Experiment Results for C14-UTCA-004G Crack A Tested at 1.0 V
Figure A.23  Processed Experiment Results for C14-UTCA-004G Crack A Tested at 0.5 V

Figure A.24  Processed Experiment Results for C14-UTCA-004G Crack B Tested at 1.5 V
Figure A.25  Processed Experiment Results for C14-UTCA-004G Crack B Tested at 1.0 V

Figure A.26  Processed Experiment Results for C14-UTCA-004G Crack B Tested at 0.5 V
Figure A.27  Processed Experiment Results for C14-UTCA-009A Crack B Tested at 1.5 V

Figure A.28  Processed Experiment Results for C14-UTCA-009A Crack B Tested at 1.0 V
Figure A.29  Processed Experiment Results for C14-UTCA-009A Crack B Tested at 0.5 V

Figure A.30  Processed Experiment Results for C14-UTCA-010K Crack B Tested at 1.5 V
Figure A.31  Processed Experiment Results for C14-UTCA-010K Crack B Tested at 1.0 V

Figure A.32  Processed Experiment Results for C14-UTCA-010K Crack B Tested at 0.5 V
Baseline Specimen Retest Set

Figure A.33  Processed Experiment Results from Baseline Retest for C14-UTCA-005K
Tested at 1.5 V

Figure A.34  Processed Experiment Results from Baseline Retest for C14-UTCA-005K
Tested at 1.0 V
Figure A.35 Processed Experiment Results from Baseline Retest for C14-UTCA-005K
Tested at 0.5 V

Figure A.36 Processed Experiment Results from Baseline Retest for C14-UTCA-008F
Tested at 1.5 V
Figure A.37  Processed Experiment Results from Baseline Retest for C14-UTCA-008F
Tested at 1.0 V

Figure A.38  Processed Experiment Results from Baseline Retest for C14-UTCA-008F
Tested at 0.5 V
Figure A.39  Processed Experiment Results from Baseline Retest for C14-UTCA-011G
Tested at 1.5 V

Figure A.40  Processed Experiment Results from Baseline Retest for C14-UTCA-011G
Tested at 1.0 V
Figure A.41  Processed Experiment Results from Baseline Retest for C14-UTCA-011G
Tested at 0.5 V

Figure A.42  Processed Experiment Results from Baseline Retest for C14-UTCB-004F
Tested at 1.5 V
Figure A.43  Processed Experiment Results from Baseline Retest for C14-UTCB-004F
Tested at 1.0 V

Figure A.44  Processed Experiment Results from Baseline Retest for C14-UTCB-004F
Tested at 0.5 V
Figure A.45  Processed Experiment Results from Baseline Retest for C14-UTCB-007J
Tested at 1.5 V

Figure A.46  Processed Experiment Results from Baseline Retest for C14-UTCB-007J
Tested at 1.0 V
Figure A.47  Processed Experiment Results from Baseline Retest for C14-UTCB-007J
Tested at 0.5 V

Figure A.48  Processed Experiment Results from Baseline Retest for C14-UTCB-010A
Tested at 1.5 V
Figure A.49 Processed Experiment Results from Baseline Retest for C14-UTCB-010A
Tested at 1.0 V

Figure A.50 Processed Experiment Results from Baseline Retest for C14-UTCB-010A
Tested at 0.5 V
Figure A.51  Processed Experiment Results from Baseline Retest for C14-UTCB-020E
Tested at 1.5 V

Figure A.52  Processed Experiment Results from Baseline Retest for C14-UTCB-020E
Tested at 1.0 V
Figure A.53  Processed Experiment Results from Baseline Retest for C14-UTCB-020E
Tested at 0.5 V
BIBLIOGRAPHY


