Vibrothermographic Crack Heating: A Function of Vibration and Crack Size

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Abstract
Vibrothermography is an inspection technique that detects cracks by observing vibration induced crack heating. Frictional crack heating in a vibrating specimen is directly linked to the resonant vibrational stress on the crack. In simple geometries we can measure the vibrational mode structure and intuit the dynamic vibrational stress field on the crack. This is used to establish a relationship between crack heating and vibration. Such a relationship will be critical for vibrothermography to be accepted as a viable inspection technology. We correlate stress to heating by exciting specimens in a well understood and repeatable resonant vibration mode. Our sample set consists of 65 Titanium and 63 Inconel specimens with low cycle fatigue cracks. Through knowledge of the mode shape, a single point surface velocity measurement is sufficient to calculate the deformed shape of the entire specimen. The loads and stresses within the specimen are calculated from the deformed shape and used to identify the relationship between crack heating and vibration. The observed relationship between normal stress, crack size, and crack heating is presented. This relationship may eventually prove viable for quantifying crack detectability in vibrothermography.

Keywords
crack detection, infrared imaging, nondestructive testing, nondestructive evaluation

Disciplines
Aerospace Engineering

Comments
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VIBROTHERMOGRAPHIC CRACK HEATING: A FUNCTION OF VIBRATION AND CRACK SIZE

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ABSTRACT. Vibrothermography is an inspection technique that detects cracks by observing vibration induced crack heating. Frictional crack heating in a vibrating specimen is directly linked to the resonant vibrational stress on the crack. In simple geometries we can measure the vibrational mode structure and intuit the dynamic vibrational stress field on the crack. This is used to establish a relationship between crack heating and vibration. Such a relationship will be critical for vibrothermography to be accepted as a viable inspection technology. We correlate stress to heating by exciting specimens in a well understood and repeatable resonant vibration mode. Our sample set consists of 65 Titanium and 63 Inconel specimens with low cycle fatigue cracks. Through knowledge of the mode shape, a single point surface velocity measurement is sufficient to calculate the deformed shape of the entire specimen. The loads and stresses within the specimen are calculated from the deformed shape and used to identify the relationship between crack heating and vibration. The observed relationship between normal stress, crack size, and crack heating is presented. This relationship may eventually prove viable for quantifying crack detectability in vibrothermography.

Keywords: Vibrothermography, Sonic IR, Sonic Infrared, Crack Detection

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INTRODUCTION

Vibrothermography also known as thermal acoustics, thermosonics, and sonic IR is a method for detecting surface cracks in engine metals. Vibrothermography uses mechanical vibration to excite the inspection component. The vibration causes friction between the faces of any cracks that are present. The friction causes a local heating in the vicinity of the crack. This local heating is imaged using an infrared camera. Vibrothermography has shown great promise as an inspection tool [1] but it lacks a set of benchmarks that can quantify the reliability of this technique.

Detecting a crack with thermography requires the generation of measurable heat. Thus in order to evaluate the probability of detection the mechanism of heat generation must be quantified [2]. Thus we seek to answer the question: Will the excitation generate vibration of sufficient amplitude to cause detectable crack heating?

It is not sufficient to simply measure the vibration and assume that the presence of vibration will cause enough crack heating to be detectable with an infrared camera. The relationship between crack heating and vibrational friction can be broken down into two parts:
First, the forces and relative motions that cause crack heating, and second the crack properties which affect crack heating. We will consider both the influences of vibration and crack size.

CRACK HEATING

It has been shown that vibrothermographic crack heating is the result of a frictional process [3]. Frictional heating is caused by vibration; without vibration there is no heating. The properties of the crack determine the frictional characteristics. The size and shape of rubbing asperities and the presence of contaminants such as oil can influence the frictional process. These parameters will generally change between cracks that are formed under different conditions. In this study we consider one Titanium and one Inconel sample set each manufactured under consistent conditions with low cycle fatigue cracks generally between 0.5-2.5mm in length.

Crack length governs the size of the contact area (crack face) that rubs during excitation. A longer crack will have more free surface area that can rub and greater relative mobility between the faces. As a result a longer crack will generally heat more. Similarly a shorter crack will have less surface area that is free to rub and will heat less. Regardless of crack size crack faces tend to be locked together near the edges of the crack face. At the edges of the crack face the relative motion is zero so there is no friction, and no friction induced heating at the edge of a crack [4].

Vibration is a direct function of the part geometry and material properties. It can be modified by variability in the excitation source, clamp conditions, and the source coupling. Because there are so many parameters that effect vibration induced crack heating it is not realistic to expect a consistent crack heating response unless all of the vibration parameters are precisely controlled. Different vibration will change the relative motion between crack faces which cause friction induced crack heating. Using a resonant vibration mode we can compensate for changes in motion by directly measuring the vibration. If the mode shape is known and the motion is measured at a single point, such as with a laser vibrometer, the motion, stress, and strain can be calculated everywhere in the part [5].

There are several properties of the crack that affect the observed crack heating, including crack size, closure stresses, and the asperities of the crack. Only crack size is controlled for this study. These cracks were formed under otherwise identical controlled conditions, so the other parameters are assumed to be constant. Thus any variation in heating caused by closure or asperity characteristics will appear as scatter in these data.

EXPERIMENT

In order to quantify the effect of stress and crack size on friction induced crack heating a set of 65 Titanium and 63 Inconel samples were tested. Each specimen had a low cycle fatigue crack ranging in length from 0.5-2.5mm in length. These samples were cut to size so that they had a third order natural frequency of 20.07kHz. The third order mode was used because it provided a consistent vibration response and a strong pure bending stress across the crack. Bending stress was calculated using elementary flexural wave theory.

The setup used in this experiment is shown in Fig 1. A tunable vibration source was coupled to the sample with card stock using a pneumatic cylinder to supply the coupling force. A single point laser vibrometer was used to measure the vibration of the specimen. The vibrometry data was used along with the known mode shape to calculate the normal
stress across the face of the crack. An emissive coating (black paint) was used to improve the thermal emission. The image sequence recorded by the infra red camera was processed using an algorithm that finds the crack and estimates the temperature rise.

The specimens were tuned to have a third order flexural (bending) resonant frequency of approximately 20.07KHz. Choosing this frequency made resonant excitation possible with both our broadband excitation system and the ultrasonic welders used by our partners. The tuning process is not perfect so the measured resonance does not always match the nominal frequency exactly. As a result we test each sample using both the nominal and resonant frequencies. This sample set was characterized to determine crack size using fluorescent penetrate inspection and optical microscopy.

Each specimen was first excited with a frequency sweep while a vibrometer measured the vibration response. This sweep was used to determine the natural frequency of the specimen. The sample was then tested six times at three different amplitudes. Three excitations, high amplitude, medium amplitude, and low amplitude, were at the measured resonant frequency of the particular sample and three were at the nominal resonant frequency of 20.07kHz. The nominal frequency was the target frequency that the samples were initially tuned to. Each of the samples was excited with the same combination of hits but the order of the hits was randomized.
FIGURE 2. Vibration induced crack heating as a function of stress in Titanium.

RESULTS

Figure 2 shows crack heating as a function of the peak to peak dynamic stress for cracks of different length in Titanium. The dashed line is the noise threshold of the camera. Temperature measurements below the noise threshold of the camera are not meaningful. As the dynamic stress increases the crack heating also increases; as the vibrational amplitude in this mode of vibration increases so does heating. The dynamic stress presented here is the result of a single frequency resonant vibration. This dynamic stress is the maximum peak to peak bending stress that acts across the face of the crack causing an opening and closing of the crack faces.

Figure 3 shows crack heating as a function of the peak to peak dynamic stress for cracks of different length in Inconel. Crack heating in Inconel follows a similar trend to that in Titanium. Both figure 2 and 3 have crack length partitioned into groups according to crack size. There is a strong correlation between crack size and heating just as there is between stress and heating. The larger cracks tend to heat more while the smaller cracks do not heat as much. In other words the smaller cracks require greater stress to generate detectable heating. This is again because the cracks are connected together around the outside edges of the crack face. Where the faces are connected there can be no relative motion. In the case of small cracks greater stress is required to get these faces to rub.

Finally figure 4 is a three dimensional representation of crack heating as a function of the peak to peak dynamic stress for cracks of different length in Titanium. Instead of grouping the cracks according to size we show size on the z axis. The yellow spheres represent detectable heat measurements. The grey spheres represent measurements below the noise threshold of the camera. The translucent surface is a power law fit of all the detectable data.

With these data it is possible to make predictions about how a crack will respond to inspection. For example in order to see a 55-75mil crack in this Titanium sample set the
FIGURE 3. Vibration induced crack heating as a function of stress in Inconel.

FIGURE 4. 3D representation of titanium data set.
dynamic stress would have to be approximately 60Mpa peak to peak at 20.07kHz. This relationship could eventually make it possible to specify a crack size and determine how to excite the specimen such that the specified crack would heat up.

CONCLUSION

This data presents a clear relationship between vibrational stress, crack length, and crack heating. While limited to the effect of frictional heating induced by normal stress on these cracks with simple specimen geometry these results provide the first quantitative data relating crack heating temperatures to the stresses applied to cracks. We have presented a technique that factors out much of the hit to hit variability in crack heating. It is less sensitive to input conditions. Most importantly this data may be useful for predicting the friction induced crack heating in useful parts. By providing a quantitative relationship between vibrational stress, crack length, and crack heating we take one step toward quantified crack detectability for vibrothermography.

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