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Frictional heating model for efficient use of vibrothermography

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ABSTRACT

This paper investigates vibrothermography for the detection of fatigue cracks in steel compact tension specimens using combined experimental and numerical analyses. First, a numerical modal analysis is carried out to predict the optimal excitation parameters. A coupled thermo-mechanical model is then built to simulate the thermographic inspection. The model predicts the detection of cracks as short as 0.1 mm that is also confirmed experimentally using a commercial infrared camera with a maximum error of 2.13% on the temperature distribution. The model reveals that the specimens' temperature increases at the crack vicinity according to the excitation frequency and is modulated due to the nonlinearity induced by the crack. The model also shows that the stress at the crack tip is lower than the material's yield stress, which makes the test truly non-destructive.

1. Introduction

Thermography is a non-destructive evaluation (NDE) technique that measures surface temperature variations of an object in response to induced energy. The energy creates a temperature contrast at materials' discontinuities that can be detected using an infrared camera. Thermography is gaining more acceptance as a fast non-contact and large area inspection technique primarily due to the recent advancements in the data acquisition and analysis systems [1]. It has been found that when using thermography for flaw detection, the analysis become particularly interesting if the energy is induced using harmonic excitation instead of the conventional excitation methods [2,3].

The term 'lock-in thermography' (LT) is used when a modulated harmonic input is employed to detect a discontinuity. Lock-in thermography has the advantage of preserving the frequency and the shape of the thermal response that enables us to calculate both the amplitude and the phase images from the Fourier transformation of the temperature response. Often, the phase image provides better detection contrast than the amplitude image since it is less sensitive to local optical features including the non-homogeneous emissivity of the inspected surface [4].

In lock-in vibrothermography, periodic stress waves are applied to the test part. Due to the conversion of the mechanical energy to thermal energy, heat is generated at discontinuities where surface friction takes place. The generated heat can be detectable by sensitive infrared cameras at the outer surface of the inspected components. Since the heat source in vibrothermography is the discontinuity itself, the identification of defects is much simpler than the passive heating methods. In this method, the resulting thermal waves propagate from discontinuity site to the surface of the inspected component as opposed to passive heating where thermal energy propagates first from the surface to the discontinuity and then back to the surface from the discontinuity resulting in large attenuation [5].

In vibrothermography, mechanical excitation devices like piezoelectric and electromagnetic shakers, piezo-ceramic actuators, air- and water-coupled ultrasonic transducers or ultrasonic welders are used as sources of energy. When using ultrasonic transducers as the excitation source, vibrothermography is referred to as ultrasonic-thermography [6], sonic IR [7], or thermosonic [8]. Ultrasonic burst phase thermography [9] is also employed when short ultrasonic bursts are used.

Vibrothermography has been studied in different aerospace applications such as the detection of hidden corrosion in monolithic aluminum components and in multi-layer riveted structures [4,6], as well as cracks in aluminum and titanium specimens [6,10]. Others have used to identify poor adhesion between ceramic coating and metal substrate [11] and to inspect the quality of adhesive bonding in composites [12] like aircraft repair patches bonded over a cracked substrates [10]. Detection of delamination, impact damage, voids, and inclusions in polymers and polymer composites have also been assessed using vibrothermography [9,12]. VT has also been used to detect defects in welded joints, brazed joints, forged components, ceramic plates, and in graphite/epoxy samples [13].

In parallel with the experimental studies, some authors have attempted to develop numerical models to increase the level of

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understanding of the fundamental mechanisms behind crack detection using vibrothermography. Finite element (FE) method has been used to investigate the effect of complex parameters, such as geometry, material properties, loads, and nonlinearities, on the process being analyzed [14]. Chinmoy used crack dynamic modeling [7] to calculate the sliding or friction energy created by the rubbing of crack faces, and to visualize the associated modes. Han et al. created a basic finite element model for a metal fatigue crack [15] to study the efficiency of chaotic vs. non-chaotic sonic excitation in generating heat around cracks. Combined structural and thermal FE analyses have also been performed [16,17] to understand the effect of applied sonic pulses at delaminated locations on the temperature variation on the monitored sample surface. A theoretical model [18] using the heat equation is solved for a semi-infinite cracked slab of finite thickness to describe the thermosonic imaging of surface-breaking and sub-subsurface cracks, together with illustrative comparisons with experimental measurements.

This paper focuses on the application of vibrothermography for crack detection based on frictional heating concept. Therefore, the mechanism of friction and the parameters associated with the resulting temperature rise are first introduced. Next, the specimen and the experimental setup are described followed by the results of the numerical modal analysis performed to identify optimal excitation parameters in specimens being evaluated. The experimental results of vibrothermography detection for different crack sizes in the same specimens are then presented. The strategy of modeling frictional heating, its theoretical aspects, and the finite element model parameters are then discussed. In the last section, the results of numerical modeling are compared to those obtained experimentally. The characteristics of the temperature evolution at the vicinity of the crack, the test non-destructivity, and the overall advantages of using vibrothermography in crack detection are also explained.

2. Frictional heating

2.1. The mechanism of friction

According to ASTM standard G-40-05, the friction force is the resisting force tangential to the interface between two bodies when, under the action of external force, one body moves or tends to move relative to the other. Friction involves the characteristics of the contact surfaces such as surface roughness, temperature, normal force, and relative surface velocity. Sliding between the two bodies occurs depending on whether the tangential force can overcome the friction force. The ratio between the tangential and normal forces is the friction coefficient. The static friction coefficient (μ_s) is generally somewhat greater than the kinetic friction (μ_k) but the difference is not usually very large [19].

2.2. The temperature rise due to friction

When a friction force F moves through a distance x, an amount of energy Fx is produced. The laws of thermodynamics state that, at equilibrium, the energy into a system equals the sum of the energy accumulated and the energy output to the environment.

$$E_{\text{syst}} = E_{\text{accumulated}} + E_{\text{lost}} \tag{1}$$

The power input in friction is the product of the frictional force F and the sliding velocity v. The input energy is balanced at the friction interface almost completely by heat dissipation away from the interface, either into the contacting solids or by radiation and convection to the surroundings [20]. In general, around 5% of frictional energy is consumed or stored in the material as microstructural changes such as dislocations and phase transformation, or surface energy of new wear particles and propagating subsurface cracks, etc [19]. The remaining part of the frictional energy raises the interface temperature locally. In frictional heating, one can distinguish between two temperatures:

- The flash (localized) temperature that is the maximum friction-induced temperature of the tips of interacting asperities.
- The mean surface (averaged) temperature that is the average temperature across the frictionally heated surface.

The combined effect of many interacting asperities dissipating their energy in the interface is to heat a near-surface layer to a higher temperature. Basically, the temperature rise at the interface is given as a function of the total heat developed, Q given by [19]

$$Q = \frac{\mu N v}{J} \tag{2}$$

where μ is the sliding friction coefficient, N is the normal applied force, v is the sliding velocity, and J is the mechanical equivalent of temperature constant (4.186 J/cal).

Some theoretical models [19,20] have been developed for estimating the temperature rise due to friction for various flow conditions. The temperature rise depends on the same parameters as friction and thermal properties of the two rubbing surfaces. These models showed that the surface temperature increases with load and speed and becomes greater for bodies with lower thermal conductivity. In addition, the time during which a surface is exposed to frictional heating will obviously affect the amount of heat it receives.

3. Experimental setup and analysis

3.1. Specimen description

The specimens used in this work are single-edge-notched AISI type O1 steel plates with the shape and the general proportions described by ASTM E399-05 standard for the compact tension specimen configuration. Each specimen has a length, width and thickness of 143, 137, and 2.7 mm, respectively. Five specimens, each having a crack of a specific length, were used. The cracks were 0.1, 1, 2, 3, and 4 mm in length. Fig. 1 illustrates a schematic drawing of a test sample.

To generate the fatigue cracks, each sample was subjected to a tension–tension sinusoidal fatigue load at the frequency of 10 Hz and at stress ratio (R) of 0.1 with a maximum load of 15.5 kN. The crack growth was monitored using a travelling microscope and the loading was stopped after the desired crack length is obtained.

3.2. Vibrothermography experimental setup

A schematic diagram of the experimental setup is shown in Fig. 2. An electromagnetic/piezoelectric dual shaker system is used to apply vibrational energy into the specimen. The shaker that has a frequency range 10 Hz–20 kHz can produce forces of a magnitude up to 1780 N. A 4-mm-diameter hole is machined in the specimens as shown in Fig. 1 by a black circle to mount the specimen onto the shaker head. The surface temperature of the area under inspection is imaged by the 320×240 FLIR ThermaCAM® SC 3000 infrared video camera operating in the 8–9 μm spectral range. The infrared camera and the shaker system are triggered simultaneously via a computer-controlled system to