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FINITE ELEMENT ANALYSIS OF HEAT GENERATION IN ULTRASONIC THERMOGRAPHY

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ABSTRACT

Vibrothermogrphy is a promising technique that uses ultrasonic elastic waves to locally stimulate defects on solids specimens and is typically applied in the aerospace and automotive industries. This technique allows for defect selective imaging using thermal waves that are generated by ultrasound waves. The mechanism involved is frictional heating or hysteresis that turns a dynamically loaded defect into a heat source, which is identified by a thermography system. This paper presents finite element modeling (FEM) of vibrothermography to obtain a comprehensive understanding in crack heating caused by local friction between crack surfaces and hysteresis. We developed Finite element model for an edge crack subjected to ultrasonic waves.

INTRODUCTION

Over recent years, many researchers have turned their attention to researching high frequency ultrasonic elastic waves. Elastic waves are capable of propagating over long distances in specimens, and tend to interact with changes such as cracks and delaminations in a workpiece[1]. Vibrothermography is a non-destructive testing method in which cracks in an object are made visible through frictional heating caused by high frequency ultrasounds. In this technique the heat is generated through the dissipation of mechanical energy at the crack surfaces by ultrasonic waves. The frequency range used for excitation of structures is typically in the range 20 kHz to 100 kHz. A schematic representation of the method is given in Figure 1. The presence of the crack may result in a temperature rise around the area and the surface close to the crack. The temperature rise is measured by a high sensitivity infrared imaging camera whose field of view covers a large area. The method therefore covers large areas from a single excitation position so it is much faster than conventional ultrasonic testing or eddy current inspection, which require scanning over the whole surface. In addition, vibrothermography can be a more convenient and reliable inspection technique for structures with complex geometries that are difficult to inspect by conventional methods. The method is also particularly well-suited to the detection of cracks that can cause problems with other techniques such as conventional ultrasound and radiography. In fact, in this technique when waves are induced into the defects, mechanical energy will decay rapidly because of the friction between the interfaces of the cracks, or the elastic properties of the crack areas which are much more different than any other areas, consequently, thermoelastic and hysteresis effects are generated. Nowadays vibrothermography is considered as a very attractive method in nondestructive testing (NDT) and many industries have an interest in its application.

However, more systematic research is required to understand the physics that exist behind the vibrothermography in order to make this approach more reliable [1-3].

FEM is used to understand the effect of induced sound pulses on damaged zones and the principles behind crack detection using vibrothermography. FEM is also used to investigate effect of complex parameters, such as geometry, material properties, loads and nonlinearities [4,5]. FEM is generally coupled with experiments. In this paper we study heat generation, which can be generated within the structure because of thermoelastic damping and friction effects. Thermoelastic effects represent energy transfer between thermal and mechanical domains following crack surface slip and wave propagation inside the specimen.

FINITE ELEMENT MODELING OF HEAT GENERATION IN CRACKS

As mentioned in introduction section, numerical approaches are useful to simulate ultrasonic waves propagation within specimen when the specimen under investigation has a complex geometry, as in many real applications. In order to simulate a vibrothermography experiment it is necessary to understand how mechanical stress waves, created by high frequencies above 20 KHz, propagate through material. The time step has to be small for both the implicit and explicit methods and small element length is required to solve accurately the model. With a large number of elements and small time steps, a large number of equations needs to be solved, so we must determine which FEM procedures are useful to obtain accurate results. In this paper, finite element analysis was conducted using Comsol and ABAQUS, which have capability to analyse ultrasonic wave propagation and can solve dynamic problems with an implicit and explicit methods, respectively. Generally, in vibrothermography, the origin of heat generation at the crack region comes from 2 sources: from the elastic deformation of the material and from the frictional heat generated between the crack surfaces. Concerning thermoelasticity, when the sample is subjected to dynamic loading with a frequency of 20Kz, the amount of heat generated in the crack is proportional to the hysteresis loop. The hysteresis loop represents the percentage of stored energy that is lost after unloading a sample. This hysteresis is strongly dependent on material properties, frequency of load cycles. In order to simulate the temperature rise in specimen we use the following equations [6]:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla.\left(k \nabla T\right) = Q_2 + Q_d \qquad [1]$$

where T presents the temperature averaged over a time period 2π/ω, k is the thermal conductivity matrix, independent of the temperature and Q_2 and Q_d are:

$$Q_2 = -\frac{1}{2} \mathrm{Re}\,al\left[T_1 Conj\left(j\omega S_{elast}\right)\right] \qquad [2]$$

$$Q_d = \frac{1}{2}\omega\eta\, \mathrm{Re}\,al\left[\varepsilon.Conj\left(D\varepsilon\right)\right] \qquad [3]$$

where j is the imaginary number, D is the elasticity matrix, ε is the strain vector.
In addition to thermoelasticity for modeling of vibrothermography, we use frictional heating as another source of crack heating. The temperature rise is interpreted in terms of friction and the coupling between thermal and mechanical problems takes place through the internal heat generation caused by the conversion of the frictional energy into thermal energy through an irreversible process. At the first step of our simulation, the contact pressure, calculated by

finite element modeling, is used as a required parameter to stimulate the heat generation in cracks. In fact, from a theoretical aspect, when the friction force F moves through a distance x, an amount of energy is produced. 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. In general, around 5% of the frictional energy is consumed or stored in the material as microstructural changes such as dislocations and phase transformation, or surface energy due to wear by rubbing of crack surfaces, etc [5]. The remaining part of the frictional energy raises the interface temperature locally. In frictional heating, basically, the temperature rise at the interface is given as a function of the total heat developed, q given by [7]:

$$q = \mu p v \qquad [4]$$

where v is the sliding velocity, μ the friction coefficient and p the pressure in the contact. The crack surfaces slip together when the structure is excited by ultrasonic waves and the amount of the contact pressure is proportional to many parameters such as static load applied by the horn, excitation frequency, material properties, etc. based on the theory mentioned above. In our research, we modeled a plate (150 x 20 x 3mm) with a 4 mm crack shown in figure 2. The analysis is performed using different amplitudes and we can observe the temperature rise in the crack area based on thermolasticity and frictional heating. In all our models, the convection heat transfer coefficient was set at 10 W/m2.k, on all sides of the modelled specimens.

MODELING RESULTS

Based on the thermoelsaticity equations, the temperature distribution in a damaged plate under dynamic loading is similar to the modeling results shown in figure 3. In such case, the amount of temperature rise is proportional to the excitation frequency and material property and also to the applied loads. From our research, we can conclude that the highest temperature increase is in the point of crack tip that is modeled by combining stress-strain analysis with the heat equations to calculate heat generated. According to this result obtain by modeling, we observed there is a limit for frequency and amplitude during vibrothermography such that dynamic loading above this limits can cause plastic deformation and also prevent the wave propagation inside the specimen. Figure 4 clearly demonstrates the influence of different amplitudes on the sample and wave propagation inside the specimen. During the modeling, an amplitude of 0.04-0.06 mm for plastic deformation was observed but did not contribute to the heating because the stresses at the crack tip never exceeded the plastic deformation limit and also because waves propagated well inside specimen as shown in figure 4. It is noticed plastic deformation in crack tip could cause a large temperature rise which is expected to have crack propagation and fatigue damage and nonlinear behavior in the frequency response. So this point should be considered during dynamic loading by high amplitude excitation in vibrothermography technique.

The rest of the modeling results is related to friction heating because relative motion between crack surfaces plays a vital role in the study of crack in vibrothermography. This is shown clearly in figure 5. According to simulation results, based on frictional heating in crack region, the amount of heat which is released by friction depends on the size of the crack surface areas and the sliding velocity with regard to the direction parallel to the contact area and also to the contact pressure and relative velocity (under the assumption of a constant sliding friction coefficient between crack surfaces as shown in figure 5).

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CONCLUSION

We developed a finite element method for crack heating and learned how to obtain sufficient vibrations in samples. In this paper we focused on the application of vibrothermography to detection of cracks based on the thermoelastcity and frictional heating and evaluated the numerical results. We observed the mechanism of friction and hysteresis and its relation with temperature rise. In thermoelastic modeling, elastic stress concentration factors depend only on geometry, mode of loading and amount of amplitude. The position of the crack can be seen clearly from the heat generated at the crack. Simulation results made us able to directly calculate and analyze the influence of the damage for the wave propagation and the temperature distribution at the crack region on the sample and explain the mechanism of heat generation and the associated temperature evolution based on different theories. Finally, this research allowed us to predict the detectability of defects in a damaged sample.

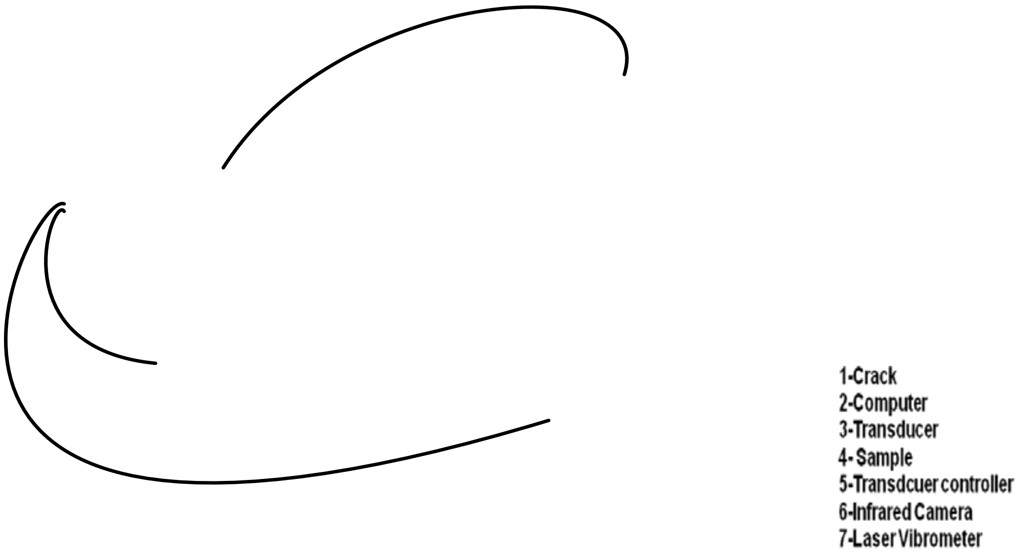

Figure 1. Principle of vibrothermography.

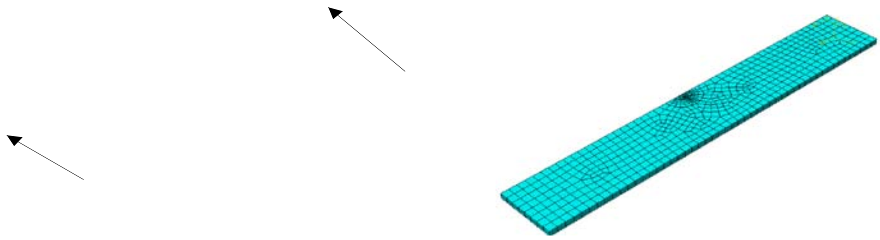

Figure 2. Geometry model for the FEM.

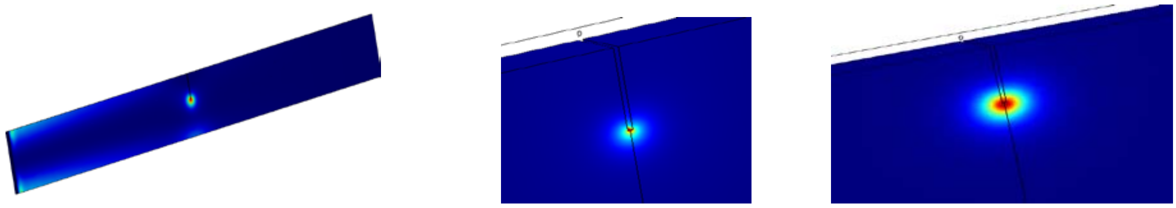

Figure 3 Simulation results of heat generation for a damaged specimen

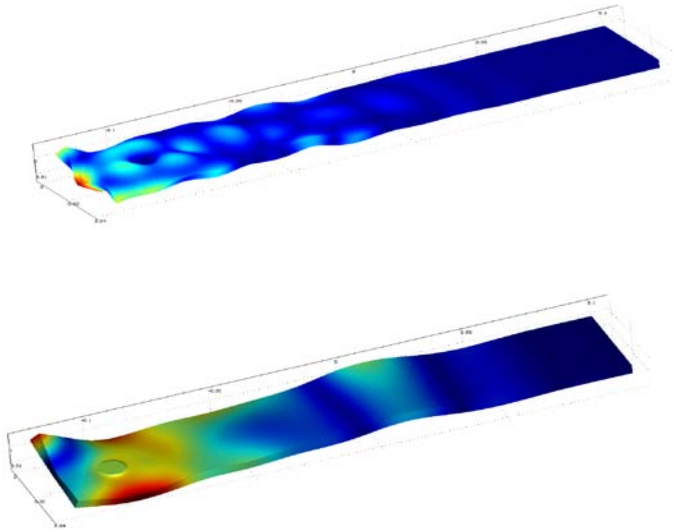

Figure 4. Simulation results of the plate to evaluate temperature rise in a crack at different excitation amplitudes.

(a) (b)

Figure 5. Slip of crack surfaces (a) Crack surfaces slip against each other. (b) Normal stress contour at the crack interface using FEM.

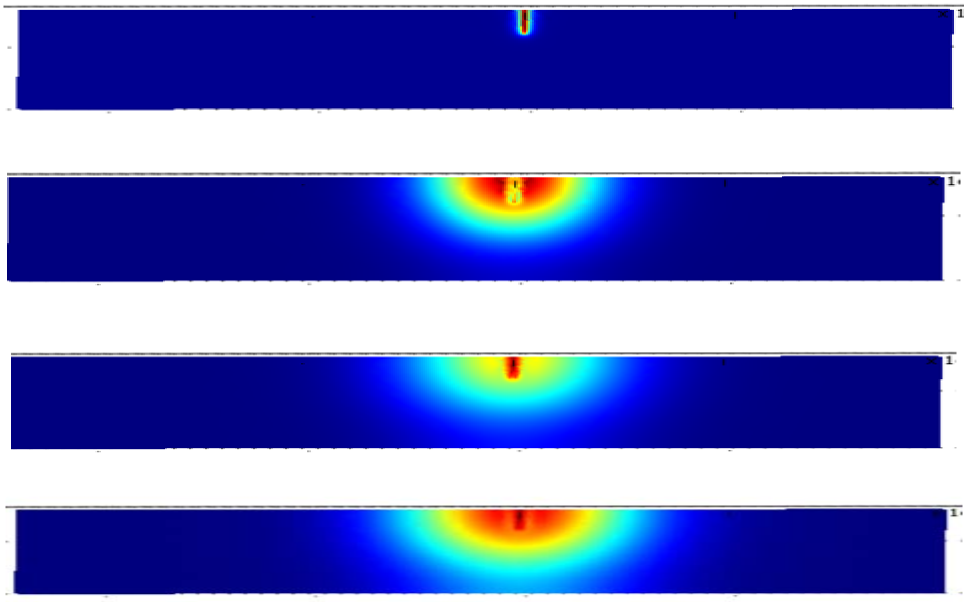

Figure 6. Numerical results of heat generation in plate with a crack, at different time steps. Heating is due to friction effect.

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