Finite element simulation of the frictional heating of cracks under excitation of intensive ultrasonic waves

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Abstract. A thermo-mechanical coupling finite element (FEM) model is built to simulate frictional heating phenomenon of a crack when the plate containing the crack is excited by intensive ultrasonic waves. In the explicit FEM model, a high-power ultrasonic transducer is included for simulating the phenomena of acoustic chaos, and piezoelectric excitation of the transducer is realized by using a piezoelectric thermal-analogy method. Moreover, the dynamical interaction between both crack faces is modelled by using contact-impact algorithm. In the simulation, Dynamical contact force and relative motion of the crack faces, temperature-rise distribution around the crack, and temperature-rise versus time curves of the crack faces, are quantitatively calculated and analyzed when the plate undergoing chaotic excitation.

1. Introduction
As a novel hybrid ultrasonic/infrared nondestructive testing technique, ultrasonic infrared imaging (UIR) has obtained much attention in recent years \cite{1,2}. For explaining the mechanism of the localized heating of cracks in UIR, several studies were presented in recent years, such as, Mian et al. \cite{3} reported a finite element (FEM) computation for the response of a fatigue damage under sonic load; Mi et al. \cite{4} presented a theory and FEM codes to calculate the heating around a crack. However, during the above researches, the ultrasonic excitation was modeled simply by a time-dependent sinusoidal displacement load at the surfaces of the sample. In other words, the high-power ultrasonic transducer system was not included in the FEM model, which leads to the phenomena of acoustic chaos \cite{2,5} can not been modeled reasonably. As a result, the simulation of crack heating may not be very accurate.

In this paper, a three-dimensional thermo-mechanical coupling FEM model is built up to simulate the frictional heating phenomena of a crack when the plate containing the crack is excited by intensive ultrasonic waves. In the explicit FEM model, a high-power ultrasonic transducer system is included for simulating acoustic chaos reasonably, and piezoelectric excitation of the transducer is realized by using a piezoelectric thermal-analogy method \cite{6}. On the other hand, the contact interaction between the both crack faces is modeled by using a contact-impact algorithm based on penalty method \cite{7}. Considering the plate undergoing sound chaotic excitation, the vibration waveform and frequency spectrum of the plate, the dynamical contact force and relative motion of the crack faces, the temperature rise distribution around the crack zone, as well as the temperature-rise versus time curve of the crack faces, are quantitatively calculated.
2. FEM modelling

The FEM model consists of an aluminum alloy plate and an ultrasonic transducer. The plate is of a size of 120×60×2.5 mm³ and has a notch at the top side. A through-thickness crack with two crack faces is located just below the notch, where the length of the crack is about 3 mm. The boundary conditions of the plate are that all degrees of freedom of the displacements are constrained at the nodes of the left and right sides of the plate. The simulated transducer is composed of six PZT-8 piezoceramic discs, a cylinder-shaped back mass and a front mass, and a composite ultrasonic horn. For describing accurately the contact interaction between both crack faces, refined meshing is adopted in the vicinity of the crack. In the model, a static coupling force is applied to the transducer to push it against the plate surface. The corresponding FEM meshing model is shown in Figure 1.

![Figure 1. FEM modeling of plate containing a crack excited by high-power ultrasonic transducer](image)

Owing to explicit integration algorithm has good stability and fast calculation capability, an explicit FEM code LS-DYNA is used here. During the simulation, the interface between the horn tip and the plate is assumed to be unbonded, where the surface of the horn tip is designated as the master side and the plate surface around the contact region is designated as slave side. For contact modeling of the crack faces, one face is declared as a master surface and the other one is a slave surface. In current model, penalty method is used in formulating the contact mechanisms and “surface-to-surface” contact algorithm is chosen [7]. Moreover, the Coulomb model is employed to simulate the friction process, where the friction coefficient between the crack faces is assumed to be 0.4. During the simulation, the initial temperature of the plate is assumed to be 27.0 °C.

Until now most explicit FEM programs like LS-DYNA are not possible to simulate the piezoelectric field, so the vibration excitation of piezoelectric transducer should be realized by other methods. In the work, piezoelectric thermal analogy method as described in Ref. [6] is used. According to the method, the strains due to an applied voltage field can be modeled by thermally induced strains. For the extension actuation mechanism of piezoelectric materials (the polarization axis of the piezoceramic is aligned with the z-axis), the correspondence between piezoelectric strains and thermal strains is obtained as follows:

\[
\begin{align*}
\alpha_{11} &= \frac{d_{31}}{t}, & \alpha_{22} &= \frac{d_{32}}{t}, & \alpha_{33} &= \frac{d_{33}}{t} \\
\alpha_{23} &= \alpha_{31} = \varepsilon_{12} = 0, & \Delta T &= \Psi_z 
\end{align*}
\]

where \(d_{mn}\) is the piezoelectric strain coefficient component, \(\alpha_{mn}\) is thermal expansion coefficient component and \(\Delta T\) is a temperature applied relative to a reference temperature, \(\Psi_z\) represents the voltage difference between electrodes of each piezoelectric disc and \(t\) is the thickness of each disc.

Equation 1 indicates that voltage actuation can be exactly simulated using conventional three-dimensional elastic elements with the thermal actuation rather than using piezoelectric elements. By comparing the result of harmonic analysis using thermal excitation with that using voltage excitation, it can be found that the vibration displacement of the horn tip under thermal excitation is nearly equal
to that under voltage excitation, where the relative error between them is less than 3%. Therefore, in explicit transient analyses, piezoelectric transducer can be modeled by piezoelectric thermal analogy method. In this work, the resonance frequency of the longitudinal vibration mode of the transducer is 20 kHz and the vibration amplitude of the horn tip under unloading condition is 80 μm.

3. FEM simulation results

![Figure 2](image2.png)

**Figure 2.** Simulation results of motions of both crack faces of a crack: (a) contact force waveform (inset) and spectrum; (b) relative velocity waveform (inset) and spectrum of two nodes.

It has been observed in the experiments [5] that a suitable static preload force may cause strong sound-chaotic vibration of the plate samples. The chaotic vibration of the plates will result in complex interaction of crack faces. Figure 2 shows the simulation results of motions of both crack faces when the plate is undergoing sound chaotic excitation (where the static coupling force is 150 N). It can be found in the inset of figure 2(a) that complex contact interaction occur in the crack faces in the process of sound chaotic excitation. The contact force waveform consists of a series of force pulses with different magnitudes, and the time intervals of the adjacent force pulses are different. Moreover, the contact force spectrum under chaotic excitation contains much rich frequency components. To produce frictional heating, in addition to have a suitable contact pressure at crack faces, it is important to find out relative motions of both crack faces. Figure 2(b) show the relative velocity of two nodes separately located at the right and left faces of the crack and 0.4 mm from crack tip. It can be found in the inset that there exists relative motion between the two crack faces. Moreover, different nodes on the same crack face have different velocity amplitudes. It also can be seen that the velocity spectrum includes many higher frequency components which helps to get higher relative velocity.

![Figure 3](image3.png)

**Figure 3.** Simulation results of temperature distributions around crack under ultrasonic excitation.
The temperature distribution around the crack area under ultrasonic excitation is shown in figure 3. It can be found that frictional heating phenomena occur on the crack faces. As the time progresses, the heat energy is dissipated at crack faces and diffuses away from the crack. As a result, the area of the bright spot becomes bigger and bigger during the excitation process. When the ultrasonic pulse is turned off at time 120 ms, an obvious temperature rise in the range of 0.7 - 0.8 °C is observed in the crack region, which makes the crack detection by UIR become easier.

The temperature versus time curves for two nodes located on the crack faces are shown in figure 4, where one node is near the crack tip and the other one is at the middle region of the crack. It can be observed that the temperature rises quickly when the ultrasonic excitation is turned on. It is also clearly seen that the temperature increment is higher in the crack middle region than at the crack tip. The reason for that is the crack middle portion has larger relative velocity between both the crack faces then more thermal energies are generated. In addition, the curves in figure 4 show that the temperatures increase un-monotonously and have some fluctuation under chaotic excitation, which is induced by the intermittent contact of the crack faces.

![Figure 4. Simulation results of temperature-time curves for two nodes located at crack face.](image)

4. Conclusion
The mechanism of crack detection by ultrasonic infrared imaging (UIR) has been further studied by using transient FEM simulation. Several typical conclusions are obtained as follows: (1) In the dynamic interaction process of crack under ultrasonic excitation, crack faces will produce relative motion, then contacting, slipping and separating will occur on the crack faces. As a result, the frictional heating is produced at the crack area; (2) Time dependence of contact force pattern across crack faces is complicated spatially and temporally. The waveform of the contact force consists of a series of delta pulses, and the magnitudes and time intervals of the force pulses are different; (3) Owing to the nonlinear interaction between the transducer horn and the sample, abundant frequency components appears in the frequency spectrums of contact force or relative velocity waveform between the crack faces; (4) Temperature-rise curves under sound chaotic excitation have some fluctuation, which just indicates that intermittent contact occurs at the crack faces. The computational results can explain reasonably the phenomena observed in UIR.

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