MODELING OF EFFECTS OF EXCITATION VELOCITIES ON THE THERMAL IMAGE OBTAINED FOR THERMOSONIC NDE

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ABSTRACT. Thermosonics is a hybrid ultrasonic – thermal technique in which the sample is excited using a low frequency ultrasonic wave. A finite difference model was constructed to study the heat transfer characteristics through the material into which different source characteristics can be introduced. Various types of heat sources that might be created due to friction were mathematically generated for various excitation velocities of the ultrasound source and the corresponding predicted thermal images are obtained.

INTRODUCTION

Thermosonics is a hybrid of ultrasonic and thermal NDE methods that has lately been shown to be useful in detecting cracks and delaminations in structures. The technique involves exciting a sample with ultrasonic waves and causing the crack surfaces to vibrate and thereby rub against each other. This rubbing friction causes the crack surfaces to heat up and this heat is conducted out through the material and can be viewed as a thermal image. This image can be further studied to detect the presence and properties of the crack/defect. The technique has been shown to be successful in many applications and has been shown to work equally well with large and small objects[1].

Fair amount of analytical modeling of the thermal part of the phenomenon had been conducted and these showed promising concordance with experimental results[2]. This paper mainly deals with a finite difference model constructed for the thermal end (from heat generation to thermal image) which takes into consideration, as a first case, a simple relationship to connect the frictional rubbing velocity with the heat generation.

FRICTIONAL HEAT GENERATION

The crack surfaces generate heat due to friction. For purposes of the model we assume that all of the heat generation is only due to sliding friction and that the heat generation intensity, that is the heat generated per unit area of the crack is given by the equation

\[ q = f \cdot p \cdot v \] (1)
Where $f$ is the coefficient of friction, $p$ is the pressure on the surface and $v$ is the sliding speed.

This equation holds true only for sliding friction. In reality the ultrasonic excitation may also cause release of energy due to sliding as well as due to other vibration modes so more complicated relationships will have to be looked into. For the purposes of modeling, it is assumed that the velocity and pressure at the crack tip is known. This is justified because there exist currently, various ultrasonic models that can predict the velocity and force fields at points inside the solid through which the waves are propagating. It is also assumed that the transfer function does not change the time dependency of the heat generation function $q$. Then it follows that the heat generation can be directly linked to the wave velocity at the crack tip which in turn can be linked to the velocity of the ultrasonic excitation.

**THERMAL MODEL**

The thermal model was developed using heat conduction formulation for a line heat source. The aim of the model was to determine the thermal image (or the temperature distribution on the outer surface of the solid object, which is being tested for cracks. The crack is assumed to behave like a line crack with heat generation intensity given by the equation 1. This heat is assumed to be conducted to the outer surface. Transient effects are neglected as a first approximation.

For the heat transfer analysis the considered portion of the geometry is divided into a number of elements. Fig (1) shows the heat balance within a small differential element of size $dx*dy*dz$ i.e. say at $(m,n,p)^h$ node where $m,n,p$ are chosen along the length, width and thickness direction of the considered portion. The heat transfer by conduction is formulated using finite difference technique. The rate equation for energy balance in a typical differential control volume can be represented by the equation (2),

$$ q_{in} + q_{g} = q_{out} + q_{e} $$ (2)
where $q_{in}$ is the rate of heat input, $q_g$ is the energy generation rate, $q_{out}$ is the rate of heat output, $E_s$ is the energy storage rate at $(m,n,p)$th node respectively. Further for each differential element the heat going into and coming out of the element can be written as below

$$q_{in} = q_x + q_y + q_z$$

$$q_{out} = q_x + q_y + q_z$$

Using the Fourier laws of heat conduction we can determine the rate of heat flowing in and out of a control volume in each direction as a function of the temperature of the elements in question. Discretizing the governing differential equation, we obtain the FDF equation shown below.\[4\]

$$\begin{align*}
(K_{\text{m,n,p}} + K_{\text{n,m,p}}) \frac{\Delta y \Delta z}{2} (T_{\text{m,n,p+1},r} - T_{\text{m,n,p},r}) + \\
\frac{\Delta x \Delta y}{2} (r_{\text{m,n,p+1},r} + K_{\text{n,m,p+1}}) (T_{\text{m,n+1,p},r} - T_{\text{m,n,p},r}) \\
+ \frac{\Delta x \Delta z}{2} (r_{\text{m,n,p+1},r} + K_{\text{n,m,p+1},r}) (T_{\text{m+1,n,p+1},r} - T_{\text{m,n,p+1},r})
\end{align*}$$

The boundary conditions employed are:

1) $K_x (dT/dx) = 0$ along $x = 0$ and $x = x_0$
2) $K_y (dT/dy) = 0$ along $y = y_0$
3) $K_z (dT/dz) = 0$ along $z = 0$ and $z = z_0$

$\epsilon_{m,n,p}, K_{m,n,p}, \rho_{m,n,p}$ and $C_p_{m,n,p}$ denote the emissivity, thermal conductivity, density and specific heat of the differential element at the $(m,n,p)$th node. The equation (4) results in $N$ number of algebraic equations when the considered portion of the wheel is divided into $N$ number of elements. The equations are solved using the LU decomposition method. The solution to the above equation can be used to find the temperatures at any points in the solution space and in particular the temperature distribution on the surface.

The mesh used is shown in Figure 2. The parameters used for the material match that of aluminum and the ambient temperature is assumed to be 300 Kelvin. The values of $f$ and $p$ in equation (1) are assumed to be 1. So the heat generation term comes out to be equal to $v(t)$.

![Crack Plane at the center of the model – considered as a plane heat source](image)

**FIGURE 2.** Mesh used for modeling thermal conduction.
MODEL RESULTS

The model results are presented in Figure 3 to Figure 6. Figure 3 shows a snapshot of the temperature distribution as a deformed mesh for constant heat input. Figure 4 shows the same temperature distribution as an intensity plot. Figure 5 shows the curve of maximum temperature on the specimen surface as a function of time for a pulse velocity input. The input curve is also shown for comparison. It is to be noted that in reality the
situation would be transient (as opposed to the steady state response that we are depicting above) and there would be a phase difference between the input and the output curves. This is not shown here because the curves are only used as a means to depict the ability of the model to return valid results for various input patterns. Similarly Figure 6 shows the same maximum surface temperature curve for a sinusoidal velocity input.

**FIGURE 5.** Response to pulse input: max temperature.

**FIGURE 6.** Sinusoidal input: max temperature.
USES FOR THE MODEL

The model can be used to determine the temperature distributions for much more complicated heat inputs and can also be modified for transient inputs. The model with the inclusion of the ultrasonic and the heat generation functions can be used as a starting point for a complete, encompassing numerical model for thermosonics. This can be used as a data bank for inverse studies to try and classify defects using thermal techniques. In other words, the location of the heat source on the plane parallel to the surface can be determined from the model temperature distribution that matches with the image from infrared sources.

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REFERENCES