MODELING AND SIMULATION FOR CRACK DETECTION IN ALUMINUM COMPONENTS USING TONE BURST EDDY CURRENT THERMOGRAPHY

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ABSTRACT. Tone Burst Eddy current Thermography (TBET) is a new hybrid, non-contacting, non-destructive evaluation method with a wide range of applications including aircraft. Aircraft can have structural cracks or other defects which can lead to failure. The safe life of structural members can be evaluated by determining the size and orientation of critical cracks. For understanding cracks, fundamental knowledge about the induced current density distribution in the component under test is required. Further, this information enables us to find the amount of heat produced at those locations and how it diffuses to the surface. This paper describes simulation work done for crack detection in aluminum samples. 3D simulation results have been achieved by using COMSOL multi-physics with AC/DC module and general heat transfer. Various parameters considered in this study are i) induction coil dimension, ii) plate dimension and iii) time of excitation for a particular crack. A comparison of results obtained by varying the above mentioned parameters is done. Numerical simulations are carried out in a plate with a part crack also. At crack edges, induced current is seen concentrated thus indicating a localized high heating in those areas relative to other regions. TBET method was found well suited for the detection of service induced cracks, usually caused by either fatigue or stress corrosion, with a high degree of sensitivity.

Keywords: Tone Burst Eddy Current Thermography, Induction heating, Thermal Imaging, Crack defect, Skin depth, Finite element analysis

INTRODUCTION

Tone Burst Eddy current Thermography (TBET) technique is a new hybrid, non-contact, non-destructive evaluation with a wide range of applications especially in aircraft industries for crack and corrosion detection under paints, cracks around the riveted joints, edge crack, in transport industries for rolling contact failures, which leads to the cracks formation in rail track heads, etc. TBET technique combines both Eddy Current testing(ECT) and Thermographic non-destructive evaluation (TNDT) techniques to provide a fast and efficient method for defect detection and characterization over a relatively wide area[1]. This technique uses induced eddy currents to heat the material being tested and defect detection is based on the changes of the induced eddy current flows revealed by the thermal visualization captured by an infrared (IR) camera. Thermographic data and thermograms can then be immediately assessed to provide an indication of major faults and the data can be further analyzed to provide quantitative information of defects inside the inspected sample.

ECT involves the application of a high frequency (typically 150–450 kHz) electromagnetic wave to the material under inspection. For TNDT a short thermal stimulation pulse lasting from a few milliseconds for high-conductivity material(such as metals) to a few seconds for low-conductivity specimens(such as plastics, graphite epoxy laminates) is used. In ECT much importance is attached to the relationship between electromagnetic skin depth(which is the depth of penetration of induced eddy current on the surface) and the defect depth, but as the skin depth formula is only applicable to perfectly flat and flawless samples, this relationship can only provide a rough guide at best. Since in TNDT we are dealing with only the distribution of surface temperature to assess the structure or behavior of what is under the surface, even if the skin depth is lesser
than the defect depth the heat produced on the surface of the sample transfers from the warm areas to the cooler ones by conduction, which effectively occurs by diffusion.

This study considers the capabilities of TBET for obtaining quantitative information about crack type damage in Aluminum plate like structures. The investigation is implemented by simulating the transient thermal distribution for cracks around rivets and edge cracks, via multiphysics 3D finite element analysis (FEA) using COMSOL multiphysics with AC/DC module and general heat transfer. Various parameters considered in this study are i) induction coil dimension, ii) plate dimension and iii) time of excitation for a particular crack. A comparison of results obtained by varying the above mentioned parameters is done. Numerical simulations are carried out in a plate with a part crack also. At crack edges, induced current is seen concentrated thus indicating a localized high heating in those areas relative to other regions. Driven by the requirement of quantitative NDE means of characterizing crack defects, a study has been made of the response of TBET to edge crack and riveted joint crack[2]. The ability to acquire quantitative information about defect geometry, i.e. depth, curved regions and length, are important for the accurate description of a defect. In this work, features from the temperature distributions of TBET investigations were extracted to gain quantitative information about edge crack and riveted joint crack.

NUMERICAL SIMULATION FOR ECT - RESULTS AND ANALYSIS

The Simulation of TBET technique requires a multi-physics electro-thermal approach involving, (a) an electro-magnetic model for the eddy-current generation, (b) an electro-thermal model for the conversion of eddy-currents into heat, and (c) the heat transfer model for the heat conduction from the heating surface into the material[3,7]. A 3D Finite Element Modeling (FEM) approach has been selected so that the model can be later extended to more complex and arbitrary configurations. All models were developed using the Multiphysics COMSOL® package version 3.5a.

Theoretical Background

Induction heating is accomplished using an electromagnetic induction coil through which alternating current at a specific frequency is applied. Whenever this primary AC passes through an electromagnetic induction coil with a certain frequency of excitation, a varying magnetic field will generate around the coil. When this electromagnetic field is applied to a conductive material placed near, an electro-magnetic force will generate which induces a current to flow through it. This induced secondary current is called eddy current. The secondary eddy-currents produced in the sample due to this primary current by induction coil causes a rise in the near surface temperature of the sample due to Joule heating. The presence of defect will disturb the eddy-current density distribution around it and hence the surface temperature distribution. A rise/fall of few degrees is expected for TBET when a defect is present. In most of the earlier reported work, continuous AC was employed at a single frequency. However, the use of tone bursts (a fixed number of cycles) and the effect of the frequency of the AC are both explored in great detail in this paper. This technique, henceforth called Tone Burst Eddy-current Thermography (TBET) uses tone burst AC pulses to locally heat a conducting material and uses a thermal imaging IR camera to map the surface temperatures.
Solving the magnetic field propagation (Eq. (1)) simultaneously with the heat transfer (Eq. (5)) is the underlying equations which governs the whole simulated system. The governing equation pertaining to magnetic field propagation is given by,

\[
\tilde{\nabla} \times \left( \frac{1}{\mu} (\tilde{\nabla} \times \tilde{A}) + (\sigma + j\omega\varepsilon)\tilde{V} + (j\omega - \varepsilon\omega^2)\tilde{A} \right) = \tilde{J}_e + \sigma(\tilde{v}_e \times (\tilde{\nabla} \times \tilde{A})) \tag{1}
\]

Where, \(\tilde{A}\) – Magnetic Vector Potential, \(\tilde{J}_e\) – Eddy-current density, \(\sigma\) – Electrical conductivity, \(\omega\) – Circular frequency, \(\tilde{V}\) – Electric potential, \(\varepsilon\) – Electrical permeability, \(\mu\) – Magnetic permeability, \(\tilde{v}_e\) – Velocity of the sample. The boundary conditions to solve the above equation are,

For all the interior boundaries, \(\hat{n}.(\tilde{H}_1 - \tilde{H}_2) = 0\) \tag{2}

For the end boundary \(\tilde{A} = 0\) \tag{3}

The eddy-currents generated by induction due to Joule heating increase the average temperature of the body. The Joule losses are given by

\[
Q = \frac{\tilde{J} \times \tilde{J}^*}{2\sigma} \tag{4}
\]

Where, \(\tilde{J}\) is the eddy-current in the sample, \(\tilde{J}^*\) is the complex conjugate of \(\tilde{J}\) and \(\sigma\) is the electrical conductivity of the sample.

The Fourier's transient heat conduction equation for homogeneous isotropic material is given by

\[
\tilde{\nabla}^2 T + \frac{Q}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \tag{5}
\]

Where \(T\) is the temperature, \(\alpha\) is the thermal diffusivity of the material, and \(Q\) is the heat source or heat sink. For the TBET simulations, the heat generated by Joule losses was incorporated into the above equation with appropriate boundary conditions to solve for the thermal profile at any arbitrary point in the solution domain as a function of time. Boundary conditions of convection and radiation are applied on both the sample and the coil through the following equation,

\[
-k \frac{\partial T}{\partial n} = h(T - T_\infty) + \varepsilon\sigma(T^4 - T_\infty^4) + Q_s \tag{6}
\]

Where \(T_\infty\) = Ambient temperature, \(T\) is the temperature of the body, \(h\) is the convection coefficient, \(\varepsilon\) is the emissivity of the body, \(\sigma\) is the Stefan’s constant for radiation, \(Q_s\) is the surface source/sink of heat.

Air domain boundary is considered as the constant temperature boundary condition with temperature equivalent to room temperature i.e.,

\( T = T_0 \), where \(T_0\) is equal to 300 Kelvin.

**Simulation Model Description**

Two types of cracks are considered for the simulation, riveted joint crack and edge crack. Schematic model used for the simulation of aluminum plate with riveted joint crack and edge is shown in figure 1(a) and 1(b) respectively. For riveted joint crack, various parameters considered are i) induction coil dimension(d), ii) plate dimension(b) and iii) time of excitation(t) for a particular crack dimension(3mm dia. rivet hole with 5mm crack length). Effect of these parameters on the thermal profile/image by varying one of them for a particular crack orientation were studied and compared. An aluminum plate of
150*100*b mm$^3$, where various plate thickness(b) considered are 1mm, 2mm, 3mm and 3.5mm. A copper wire of 60mm length and diameter d(which varies from 1 to 6mm) was used and the entire sub-domains are surrounded by an air domain of dimension 250*220*150 mm$^3$. A constant lift-off distance of 5mm was used for the coil. For Edge crack modeling, an aluminum plate of 220*50*2 mm$^3$ and a hollow copper induction coil of outer radius(R) 2.4mm, inner radius 1.9mm and length 12mm was used. Lift off used was 5mm.

**FIGURE 1.** FEM model of the circular induction coil on an Aluminum sample that was used in the simulation having (a). Riveted Joint crack (b) Edge crack.

**Simulation results and analysis**

Numerical simulation results obtained for riveted joint crack by varying the parameters; induction coil diameter, excitation time and plate thickness are studied. As the coil diameter increases from 1mm to 4mm there is no much variation observed in the thermal contrast but a similar higher thermal contrast pattern is seen at the crack tip (Figure 2.a) for each case. Higher thermal contrast at the crack tip is because of the increased current density concentration at the crack tip (Figure 2.b). A high current density distribution contributes a greater Joule heating results in high heat generation at those regions. Thermal contrast at the crack tip is visible more clearly at lower excitation times(10-50milli sec) and is observed distributing around it as the excitation time proceeds(Figure 3.a). As the plate thickness increases, temperature contrast is seen reducing at the transmission side for a constant lift off(Figure 3.b).
**FIGURE 2.** Numerical simulation results obtained for Aluminum plate having riveted joint crack (a). Comparison of thermal images for various coil diameter (b). Image showing current density concentration at crack tip.

**FIGURE 3** Comparison of thermal profile obtained for Aluminum plate having riveted joint crack for (a). Various time of excitation (b). Different plate thickness.
FIGURE 4. Thermal images and profile obtained for Aluminum plate having edge crack for different excitation time in (a). Transmission mode (b). Reflection mode.

For edge crack, thermal profile obtained at the crack tip is plotted for different excitation time. A higher temperature contrast at the crack tip is clearly visible at 50milli sec and as the excitation time passes heat flux is shown spreading around the crack tip. Simulation is carried out both in transmission and reflection mode(Figure 4.a and 4.b respectively) and for each case transient thermal profile is plotted for different excitation time. Reflection mode is shown sharp peak temperature compared to transmission mode.

CONCLUSIONS

An NDT technique, TBET was found useful technique for characterizing and quantifying cracks around the edges of plates and rivets, which are found common in aircraft components. Simulations were carried out for a particular dimension crack made at plate edge side and rivet edge and the results were studied and compared for various parameters; coil dimensions, time of excitation and plate dimension.

Current density is found concentrated around the crack tip and circular rivet sides that results in the high joule heating around those areas and can be well seen as a high thermal contrast regions in thermal profiles. Thermal contrast is well observed at lower excitation time for a particular frequency(typically of few kHZ) and heat flux will get distributed around the crack tip as excitation time proceeds. Variation of induction coil dimension is not affecting much the thermal contrast at lower excitation times. Also as the plate dimension increases the thermal contrast at the transmission side is seen decreases for a constant lift off.
REFERENCES


