Tone Burst Eddy Current Thermography (TBET) for NDE Applications

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Abstract
The Eddy Current Thermography is an evolving non-contact, non-destructive evaluation method with applications especially in aircraft industries. It involves two approaches (a) the volumetric heating of the specimen and the observation of additional heating at defect locations due to Joule heating (called eddy-therm) and (b) the use of high frequency eddy current bursts for the transient surface/near surface heating of the objects and sensing the propagation of a “thermal wave” using a high sensitivity infra-red (IR) camera (Tone Burst Eddy-current Thermography-TBET). In this paper, a study on the optimum frequency of eddy current excitation which will give a maximum temperature rise for a given thickness has been conducted using both modeling and experimental techniques. COMSOL 3.5 was used to solve the coupled equations of electromagnetic induction and heat transfer. The dependency of this optimum frequency (peak frequency) on thickness, electrical conductivity, and thermal response of the sample (both plate and pipe geometries) are studied. The effect of thickness loss relative to the coil inner radius is looked in to. The thermal responses of defective samples obtained by simulation are compared with experimental results.

Keywords: NDE, induction heating thermography, Tone Burst Eddy current Thermography (TBET), peak frequency optimization.

1. Introduction
The process of induction heating consists of development of eddy currents in a conducting material by electromagnetic induction and generation of heat by Joule heating. The heat diffuses in the material and the temperature on the surface of the specimen changes [1,2]. The transient temperature behavior on the surface of the specimen, and the influence of the “thermal wave” that diffuses into the medium on the surface temperature, is picked up by a sensitive thermal imaging equipment (such as an IR camera) and used for detecting and characterizing surface and sub-surface defects. Pulsed thermographic NDT has been previously well reported [3-7] and is based on the rapid heating of the surface of an object using either a laser or a flash lamp and transient mapping of the surface temperature, either on the same side or on the opposite side, using a high-speed, high-sensitivity, infrared (IR) camera. Heat diffusion into the material, when perturbed by the presence of a subsurface defect, causes a local temperature contrast (between the defective and the non-defective regions) on the measuring surface. This temperature contrast is detected by the thermal imaging equipment. Recorded images over several time frames are processed for extracting the internal flaw information.

An alternative method using induction based (eddy-currents) heating for thermography is being explored for surface and subsurface crack detection [8-14], and for applications in the lock-in thermography mode [15]. Several analytical/numerical models are reported on the induction heating process [16-18]. H. Chen et al. [19] used a mathematical model for high frequency induction heating and studied the effects of heating parameters such as the coil lift off, applied current, the frequency, and the turns of the coil on the temperature histories. The study pertains to a specimen without any defect. The results obtained by simulation were verified by experiments. Recently, Kiran Kumar et al., [20,21] discussed the application of Tone Burst Eddy current Thermography (TBET) that employs a surface heating using high frequency eddy currents and compared it with the flash thermography method. The paper describes the temperature profiles of non defective samples of different materials and also of a sample with a flat bottom defect. In [13,14], the method of using induction based volumetric heating based thermography is being explored for surface and subsurface crack detection.

Most efforts on the use of eddy current heating for NDT have been concentrated on volumetric heating of the sample and observing the Joule heating at the crack surface. Recently, the use of high frequency for surface heating, and the use of “thermal wave” that diffuses into the sample (similar to the pulsed thermal imaging) called the Tone Burst Eddy current Thermography (TBET) is being explored. For both approaches, the surface and subsurface heating zones and the efficiencies of material heating and the subsequent retrieval of relevant information for the non-destructive evaluation of materials and components will require the use of optimum frequency of the eddy current excitation. In the present paper, the dependence of frequency on the thickness of the material, on the electrical conductivity, and on the amplitude of thermal response of the sample has been studied.
in detail using a Finite Element model and verified using experiments. An attempt is made to find the thermal response of a defective Aluminum sample by simulation and compare it with the experimental results. The study was done using a specimen with sixteen EDM notches which simulate the effects of wall thinning defects of different diameters and depths. The influence of defect size on the temperature history is studied and effect of coil diameter relative to the defect diameter is also looked into. The simulation is done by COMSOL 3.2 multi physics software.

2. Mathematical Model

The mathematical model for the electromagnetic induction is given by the Maxwell’s equations together with the constitutive equations and Ohm’s law.

Using the definition of potentials

\[
B = \nabla \times A \\
E = -\nabla \psi - \frac{\partial A}{\partial t}
\]

(1)

the Ampere’s law can be written in the form

\[
\sigma \frac{dA}{dt} + \nabla \times \mu \nabla \times A + \sigma \nabla \psi = J' + \varepsilon \frac{d^2 A}{dt^2}
\]

(2)

where \( E \) is the electric field intensity (V/m), \( B \) is the magnetic flux density (T), \( A \) is the magnetic vector potential and \( \psi \) is the electric potential, \( J \) is the external current density (A/m²), \( \varepsilon \) is the permittivity of the medium (F/m) = \( \varepsilon_0 \varepsilon_r \), \( \varepsilon_r \) is the relative permittivity , \( \varepsilon_0 \) is the permittivity of free space = 8.854x10⁻¹² F/m, and \( \sigma \) is the electrical conductivity (S/m).

For axially symmetric structures with current passing only in the angular direction, the problem is formulated by considering only the \( A_{\phi} \) component of the magnetic potential. The gradient of electric potential can be written as

\[
\nabla \psi = -\frac{V_{\text{loop}}}{2\pi r}
\]

(3)

since the electric field is present only in the azimuthal direction. \( V_{\text{loop}} \) is the potential difference for one turn around the z-axis. For time harmonic analysis \( A = A_{\phi} e^{j\omega t} \), (2) takes the form

\[
(j \omega \varepsilon \sigma - \omega^2 \varepsilon_r \mu_r) A_{\phi} + \nabla \times (\mu \nabla \times A_{\phi}) = \sigma \frac{V_{\text{loop}}}{2\pi r} + J'
\]

(4)

The boundary conditions are magnetic insulation on the domain boundary,

\[
A_{\phi} = 0
\]

(5)

and continuity of magnetic fields on the interior boundaries,

\[
n \times (H_1 - H_2) = 0
\]

(6)

The heat generated within the plate is taken as [22]

\[
Q = \frac{1}{2} \sigma |E|^2
\]

(7)

For an axi-symmetric problem, the heat transfer equation is expressed by

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( k r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left( k \frac{\partial T}{\partial \phi} \right) + \dot{q} = \rho C_v \frac{\partial T}{\partial t}
\]

(8)

where \( \rho \) is the material density (Kg/m³), \( C_v \) is the specific heat (J/Kg. K), \( T \) is the temperature (K), and \( k \) is the thermal conductivity (W/m. K).

The boundary conditions used are prescribed temperature at the domain boundaries,

\[
T = T_a \quad \text{(Ambient Temperature)}
\]

(9)

and heat flux at the other boundaries

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

(10)

Where \( h \) is the convective heat transfer coefficient (W/m².K), \( T_\infty \) is the ambient temperature (K), and \( \varepsilon \) is the emissivity , and \( \sigma \) is the Steffan-Boltzmann constant = 5.67x10⁻⁸ W/m²K⁴.

3. Experimental Set up

The experiments were performed on two Aluminum plates. One was of 1 mm thickness without any defect and the other with thickness 1.7 mm with wall thinning defects of 30 mm, 20 mm 10 mm, and 5 mm diameter with defect thickness of 1.25 mm, 1.45 mm, 1.55 mm, and 1.65 mm in each case [23]. The coil was made by winding copper wire of gauge 26 on a bobbin with around 100 turns. The lift off of the coil from the sample was approximately 2 mm. A current of 12 A was passed through the coil for 3 s and the temperature history of the surface was monitored for 6 s. A power amplifier PA 52A was used to amplify the input power to the coil. The experiments were repeated for different frequencies. An infrared camera with a sensitivity of ±0.1° was used to measure the temperature on the top surface of the specimen. The camera was placed on the same side of the coil (reflection mode). A schematic diagram of the experimental set up is shown in Fig.1.

![Fig. 1: Schematic diagram of the experimental set up](image-url)
4. Simulation Studies

The coupled electromagnetic and temperature field equations were solved using COMSOL 3.5 multi physics software. Axial symmetry was made use of in the analysis. The loop potential was calculated from the current passing through the coil (in the experiment) and its resistance and was approximately equal to 0.25 V. Simulation studies were carried out for different time of heating and finally arrived at a time of heating of 3 s and the period of observation 6 s. The smaller the time of heating, the lesser the temperature rise. Higher values for excitation time are not used to avoid overheating of the amplifier during experiments. The trials were repeated for different frequencies. The coil was modeled by Copper wires of 0.3 mm diameter in 25 x 4 arrangements as shown in Fig. 2. The specimen was made of aluminum. Both the coil and the specimen were placed in air domain. Simulation studies were carried out for both defective and non-defective samples. Figure 3 finite element discretisation of the model.

The material properties and constants used for the simulation studies are listed in Table 1.

The Boundary conditions used for the electromagnetic induction were

1) Axial symmetry at r=0
2) Magnetic insulation at the air boundaries (AΦ=0)
3) Continuity of magnetic fields at the interior boundaries \( n \times (H_1 - H_2) = 0 \)

and for the heat transfer,

1) Axial symmetry at r=0
2) Temperature boundary condition at the air boundaries \( T = T_a = 300 \, K \)
3) Heat flux at the other boundaries
\[
\left[ k \frac{\partial T}{\partial n} = h(T_c - T) + \varepsilon \sigma (T_c^4 - T^4) \right].
\]

The thermal signatures of the sample were monitored at point 1.

5. Results and discussion

5.1 Simulation studies on an Aluminium plate without defect

Figure 4 shows the simulation temperature history of point 1 on the top surface of 1mm thick Aluminum sample without any defect for different frequencies of excitation. It is observed that there is an optimum frequency \( f_m \) at which the temperature rise is the maximum.

Peaking takes place for 1 s duration pulse as well as for any higher value say 3 s duration. The peak temperature increases with duration. The frequency at which peaking takes place is the same for any duration pulse. All these trends are observed in volume heating regime. For each

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Air</th>
<th>Aluminium</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permeability, ( \mu_r )</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Electrical Conductivity, ( \sigma ) (S/m)</td>
<td>0</td>
<td>3.774x10^{-7}</td>
<td>5.998 x10^{-7}</td>
</tr>
<tr>
<td>Thermal Conductivity, ( k ) (W/m. K)</td>
<td>0.026</td>
<td>160</td>
<td>400</td>
</tr>
<tr>
<td>Density, ( \rho ) (Kg/m^3)</td>
<td>1.23</td>
<td>2700</td>
<td>8700</td>
</tr>
<tr>
<td>Specific Heat, ( C_p ) (J/kg. K)</td>
<td>1005</td>
<td>900</td>
<td>385</td>
</tr>
<tr>
<td>Constants</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convective Coefficient, ( h ) (W/m^2. K)</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Emissivity, ( \varepsilon )</td>
<td></td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Ambient Temperature(K)</td>
<td></td>
<td></td>
<td>300</td>
</tr>
</tbody>
</table>
frequency $f$, the local maximum temperature ($T_{f}$) occurs at or greater than the time at which heating takes place. The local maximum temperatures ($T_{f}$) for each frequency was found out and normalized with the highest value ($T_{max}$) of the $T_{f}$'s and the normalized maximum temperature is plotted as a function of frequency in Fig.6 and a comparison is made between simulation and experiment. A small input voltage was found to be sufficient to produce a measurable change in temperature.

For high electrical conductivity values, the peak frequency is more clearly observable. For low electrical conductivity values, the peak is less predominant. There can be a wide range of frequencies for which there is no considerable temperature change. The simulations are repeated with electrical conductivity values of $6.5 \times 10^7$ S/m (Silver) and $0.25 \times 10^7$ S/m (Zirconium). The optimum frequency ($f_{m}$) is found to be 900 Hz and 4800 Hz respectively. The peak temperature attained in each case with different loop potential is shown in Fig.7. The effect of thermal diffusivity on the optimum frequency is also studied. It was noticed that the thermal diffusivity has little influence on the optimum frequency because of volume heating and because of long exposure, heat diffuses several times across the thickness.

5.2 Variation of optimum frequency ($f_{m}$) with different thickness and electrical conductivity values of the sample

The optimum frequency values for different sample thicknesses and electrical conductivities of the material, keeping all other parameters same, are plotted in Fig. 8. Three electrical conductivity values used are that of Silver ($6.5 \times 10^7$ S/m), Aluminium ($3.774 \times 10^7$ S/m), and Iron ($1.1 \times 10^7$ S/m). The values of peak frequencies are plotted against the non-dimensional log ($\delta/T$) values. Here, skin-depth ($d$) is computed.

Fig. 4 : Simulation results of the temperature history of point 1 on the top surface of 1 mm thick Al sample without any defect for various frequencies of eddy current excitation.

Fig. 5 : Simulation results of the temperature history at point 1 on the top surface of a 2 mm thick Al sample, without any defect, for various excitation frequencies. The heating time was 3 s and excitation voltage was 0.25 V.

Fig. 6 : Experimental verification of optimum frequency in a) 1 mm aluminum plate

Fig. 7 : Peak Temperature vs. Loop Potential curve for materials of high and low electrical conductivity values.

Fig. 8 : Simulation results of variation of peak frequency with log($\delta/T$) for different electrical conductivity values. $K=160 \text{ W/m}. \ K \cdot \text{Cp}=900 \text{ J/Kg. K. density}=2700 \text{ Kg/m}^3$
using the standard expression \( \frac{1}{\sqrt{\sigma t}} \) where \( f \) is the frequency of excitation, \( \sigma \) is the electrical conductivity of the specimen, and \( \mu \) is the permeability of the specimen.

For volumetric heating (\( \delta t > t \)) i.e. where the skin depth is greater than the thickness), the peak frequency \( f_m \) is dependent on \( \delta t/T \) ratio as well as the electrical conductivity \( \sigma \). For non-volumetric or surface heating \( (\delta t < t) \) this frequency is found to be invariant to \( \sigma \) and \( t \) for a given coil configuration. The volume of heating, if the most efficient heating is desired, depends only on the skin depth and becomes a function of the materials electrical conductivity only. Any variations in the depth of heating can be accomplished at sub-optimal frequencies i.e. only by sacrificing the efficiency of heating.

When the defect radius is more than the inner radius of the coil (\( d_d > r_d \)), a shift in the optimum frequency was also observed (Fig.11). But when the defect radius is less than the coil radius such a shift in optimum frequency was not visible. But there was a change in the peak temperature (Fig.11). Thus by observing the peak temperature and the optimum frequency of excitation, one can detect the presence of metal loss/addition.

6. Experimental study with defective plate

The optimum frequency shift was observable in experiments also. Figure 12 shows the optimum frequency value obtained when a coil of 10 mm inner radius \( r_d \) was placed over a wall thinning defect of 14 mm radius \( r_d \) and
1.25 mm defect thickness \( t_d \) made in an aluminum plate of 1.7 mm thickness. For the no-defect case, the optimum frequency value was 900 Hz which changed to 1200 Hz for the defective plate.

7. Simulation studies with pipe geometry

Simulation studies were carried out with a 1 s tone burst signal with 0.5 V excitation potential. The trials were repeated for different frequencies. The coil was modeled by 1 layer of copper wire of 0.25 mm diameter and was placed inside the pipe as shown in Fig. 13. The stand-off distance of the coil from the inner surface of the pipe was about 2 mm. The inner diameter of the pipe was 12 mm and length 50 mm. Both the coil and the specimen were placed in air domain. Copper was selected as the material for the pipe. Axial symmetry was made use of in the analysis.

Simulations were done for different thicknesses of copper pipe starting from 0.1 mm to 10 mm with different excitation frequencies. For each thickness, there existed a frequency for which the temperature rise at the surface of the pipe is a maximum. As in the case of plate geometry, this optimum frequency \( f_m \) was unchanged for thickness of the pipe greater than the skin depth \( \delta \). Figure 14 shows the variation of the optimum frequency with thickness of the pipe. The optimum frequency followed an inverse relation with \( (\sqrt{\sigma d}) \) for cases where \( \delta > d \) as shown in Fig. 15. For pipe thickness more than 2 mm, the optimum frequency was found to be around 3250 Hz for this coil geometry.

The numerical study was repeated for an aluminum pipe with two different wall thicknesses. For half of the length, the thickness was 2 mm and for the other half 1.5 mm. The temperature contrast between the thicker and thinner regions was found out for different excitation frequencies. At the optimum frequency, the contrast was found to be the maximum (Fig. 16).

Fig. 12: Experimental results showing the shift in the optimum frequency when the coil is placed over the defect. Coil radius is 10 mm, the defect radius is 14 mm and defect thickness 1.25 mm, aluminum plate thickness 1.7 mm.

Fig. 13: Model used for simulation of pipe geometry.

Fig. 14: Simulation results showing optimum frequency for different thicknesses of copper pipe.

Fig. 15: Optimum frequency vs. \( \frac{1}{\sqrt{\sigma d}} \) for cases \( \delta > d \) in a copper pipe.

Fig. 16: Normalised temperature contrast between the thicker and thinner regions of an aluminum pipe for different excitation frequencies.
8. Experiments with Pipe Geometry

A coil was designed for the induction heating thermography of pipes of small diameter. The coil was wound with copper wire of 36 SWG, along the length of a non-conducting central core. Figure 17 shows the coil and the stepped aluminum pipe and Fig. 18 shows the schematic of the experimental set up. The excitation was given for 1 s duration. The temperature history of two points on the surface of the pipe, one each in the thicker and thinner sides, is shown in Fig. 19. The data were acquired at 200 Hz frame rate. The temperature profiles clearly distinguish the regions with thickness changes. Convective heat loss boundary condition was used in the simulation model at the inner surface of the pipe and the coil. During experiments, it was found that the heat loss from the interior is very small, because of the small diameter of the pipe as well as the central core. Hence, the temperature profiles obtained are different. It took more time to cool down during experiments. Therefore, only a qualitative comparison is made here.

9. Conclusions

Based on an axi-symmetrical FE model used for simulating the temperature field developed during the induction heating of an electrically and thermally conducting plate like material, the following conclusions can be made:

(a) Excellent correlation between simulation and experimental results verifies the validity of the FE model.

(b) Simulation studies showed the existence of an optimum frequency ($f_m$) of excitation at which the temperature reaches a maximum value, which was verified in the experiments.

(c) The optimal frequency ($f_m$) was found to be dependent on the electrical conductivity. For low electrical conductivity values, the peak temperature occurs over a wide range of frequencies. As the electrical conductivity increases this range narrows down.

(d) The effect of thermal properties on this peak frequency was found to be negligible.

(e) When there is a metal loss or deposit of radius less than the coil inner radius, the peak temperature varies linearly. But when it is of size larger than the coil radius, the variation becomes non linear. Also a shift in the optimum frequency was observed in the latter case. It was found that for defect radius ($r_d$)<coil radius ($r_c$), the sensitivity for the detection of defect is relatively small when compared to $r_d>$r_c.

(f) The optimum frequency depended on the electrical conductivity and thickness of the materials. When the skin depth is less than the thickness of the material (surface heating), the optimum frequency was found to be independent of the material properties for a given coil geometry. A rule of thumb relationship was developed to predict the optimum frequency in the volume heating regime (skin depth is greater than the thickness of the plate). The presence of a wall thinning defect, with diameter greater than the inner diameter of the coil, changed the optimum frequency.
References