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Pulsed Thermography Simulation: 1D, 2D and 3D Electro-Thermal Model Based Evaluation

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Abstract

Pulsed thermography is a popular NDT method in which temperature decay at the surface of a material is captured after heating with a small duration pulse. The present work utilizes the analogy between electrical and thermal quantities in the form of electro-thermal models for one-dimension (1D), two-dimension (2D) and three-dimension (3D) simulations of active thermography. An attempt has been made to compare and analyze results of the simulations of these models for mild-steel and carbon-fibre reinforced plastic (CFRP) samples. Decay in amplitude with depth as well as the effect of lateral heat diffusion as we progress from 1D to 2D to 3D is brought out.

Keywords: *Pulsed thermography, Mild steel, CFRP, SPICE, 1D, 2D, 3D*

1. Introduction

The active thermography process utilizes an external stimulus to reveal sub-surface features in a test specimen [1-7]. This paper presents 1D, 2D, 3D electro-thermal modeling and SPICE simulations for pulsed thermography [1]. Heat conduction in 1D is modeled by dividing the material into smaller elements along its length. Each element has its corresponding equivalent R and C values obtained from electro-thermal model. Similarly for 2D and 3D models elements are made by dividing further along the cross-sectional dimensions. To model transient heating of the sample, current sources are employed followed by SPICE simulation [7].

Simulation results are reported and analysed following the above approach. The decay in amplitude as well as thermal propagation delay of thermal waves is examined. Variations in the simulated results are shown to be attributable to differences in the models.

2. Electro-thermal Approach to Pulsed Thermography

From electro-thermal considerations, the RC equivalent [1,7,8] of a sample is calculated utilizing the equivalence between the elementary laws of heat and electricity. The heat conduction problem is thus converted into an equivalent electrical problem, where, voltage plays the same role as tempera. In the present case the electrical equivalent values of the resistance (R) and capacitance (C) for the mild steel and CFRP sample are calculated using the well-known relationship [1]

$$R = \frac{l}{KA} \tag{1}$$

$$C = \rho c A l \tag{2}$$

Here *l* is the distance from top surface (length, m), *A* is the area of the defect (m^2), *K* is the thermal conductivity (W/m°C), ρ is the density (kg/m^3) and *c* is the specific heat of the material (J/°Ckg). The heat conduction can be modeled in all dimensions by dividing the cross section areas into appropriate smaller elements. Each element has its corresponding equivalent R or C value (Eqs. 1 & 2).

3. Electo-thermal Circuit for Heat Conduction

Heat flow through a thermally conductive material can be described by 'gradient transport' which depends on three quantities: material conductivity, cross-sectional area of the material, and the spatial gradient of temperature. The larger the conductivity, gradient, and/or cross-section, the faster the heat flows.

In forming the equivalent electrical circuit the following analogy is used [1,7].

$Q = \Delta T/R_{th}$ (Heat transfer side)

↔

$I = \Delta V/R$ (Electrical side)

Here q, ΔT and R_{th} are the rate of heat transfer; temperature difference and thermal resistance (in thermodynamic units), and I, ΔV and R are the current, voltage difference and electrical resistance (in electrical units) correspondingly.

3.1. One-dimensional heat transmission

In this case, flow of heat through is simulated as a one-dimensional, time-dependent process along the x-axis (dimension) only of the sample. Heat flow in the y-direction and z-direction is assumed to be negligible.

Based on electro-thermal analogy, the heat conduction can be made by dividing the length into smaller section, with corresponding R and C value for ach section. Figure 1 shows the equivalent electrical model of 1D transient heat conduction. The current source simulating a heat source has been provided at one end of the sample model. The complete length has been divided into smaller parts. A convection resistance R_{conv} can be connected at the end of each RC node.

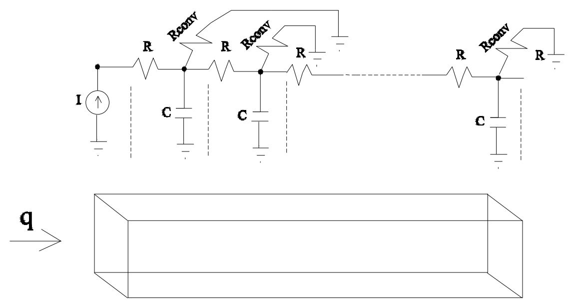

Fig. 1: One-dimensional equivalent electrical model of heat conduction

By considering the effect of other modes of heat transfer i.e. convection. The equivalent electrical resistance, which is corresponding to the thermal resistance offered by convection mode of heat transfer, is called convection resistance. Convection can be modeled by an equivalent resistance [1] if their respective coefficients are known.

R_{conv} models heat loss due to convection from the sample surface and can be calculated from the concept of convection heat transfer as:

$$R_{conv} = \frac{1}{\bar{h}S} \tag{3}$$

Here *S* is the surface area and $\bar{h}$ is the convective heat transfer coefficient. The heat transfer coefficient *S* depends on the temperature, physical dimensions, and position of the surface.

3.2. Two-dimensional Heat Transmission

The same approach of 1D modeling is extended to 2D, by considering the sample as a 2D entity (Figure 2). In this modeling, the surface of the sample parallel to the direction of incident convection has been divided into smaller elements and their R and C values calculated (Eqs. 1 & 2). As in the 1D case, the surface elements in front of incident radiations are connected to current sources (proportional to incident heat flux and surface area of the element).

The 2D model is a link between 1D and 3D models, and has its own limited significance.

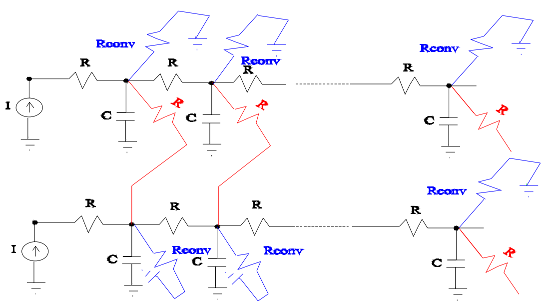

Fig. 2: Two-dimensional equivalent electrical model for heat conduction

3.3. Three-dimension Heat Transmission

Heat conduction in the sample can be further modeled by dividing it into small cuboids as shown in Figure 3. Electrically equivalent resistances and capacitances in the different directions of the cuboids are shown in the figure.

Correctly connecting all cuboids forms a 3D RC network of the sample. Elements of the front surface are connected with the same valued current sources.

Based on this approach even multi-layered samples can be modeled by adopting appropriate R and C values in different directions.

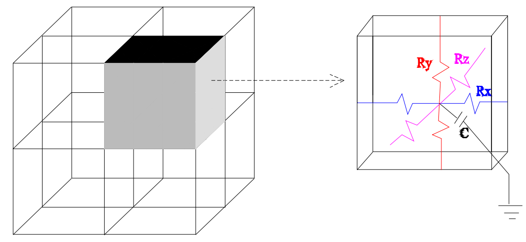

Fig. 3: Three-dimensional equivalent electrical model for heat conduction

4. Sample information

Mild steel and CFRP (Carbon Fiber Reinforced Plastic) samples have been considered for comparison. These two materials have been considered due to their varying thermal properties.

4.1. Mild-Steel and CFRP

The simulated mild-steel sample has the following dimensions: 10.4 cm length, 9.9 cm breadth and 1 cm thick. The CFRP sample is 25.2 cm in length, 15.5 cm in breadth and 0.4 cm thick. The CFRP laminate reinforcing consists of bonding the CFRP strips with a high-strength epoxy resin as the adhesive. Both of the samples are shown in Figure 4.

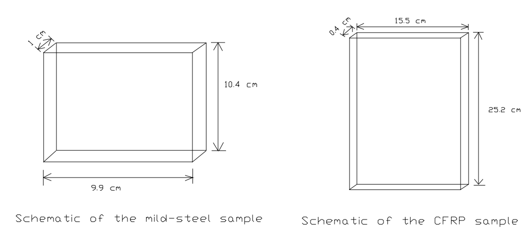

Fig. 4: Dimensional layouts of the (a) Mild steel, and (b) CFRP samples

5. Simulation

Transient (pulsed) regime has been adapted for this simulation, which in practice would consist of flash lamp for generating the heat pulse and a high speed IR camera system for data collection and analysis. Both samples have been divided into 2 × 2 × 2 sections, each, and the RC network generated from the electro-thermal modeling has been simulated by a well-known circuit simulator SPICE (Simulation Programming with Integrated Circuit Emphasis). The simulation was performed on an evaluation version of PSPICE, which has limitation of 64-nodes. RC values of each element were calculated individually. The convection resistances were used at boundaries of the RC network to model thermal insulation at boundaries and to make the circuit complete for simulation.

Incident heating on the sample has been modeled through current sources: duration 15s (including rise and fall times of 1s each) with pulse amplitude 10 ampere [8]. Heating is along length (across 20 pieces) i.e. heating is on the surface (breadth × thickness). During simulations heat/current stimulation parameters are kept same to facilitate proper comparison.

Having modeled the sample in terms of *R*, *C* and *I* elements, SPICE based simulation of the circuit is undertaken, similar to earlier reports [7,8]. SPICE calculates voltages (temperature) at every node of the circuit as well current (heat flow) through all elements. In our study the node adjacent to that of the heat source node has been taken into consideration. A transient analysis deals with the behavior of these parameters as a function of time.

5.1. Consideration of anisotropy

Many materials are anisotropic. For CFRP, parameters such as density, specific heat and thermal conductivity are different in directions parallel and perpendicular to the fibers. In this approach the effect of anisotropy in CFRP material can be modeled. The R, C values will be different according to the direction of the fibers.

6. Results and Discussions

It is important to evaluate the thermal evolution predictions among the three models for both the mild-steel and CFRP samples.

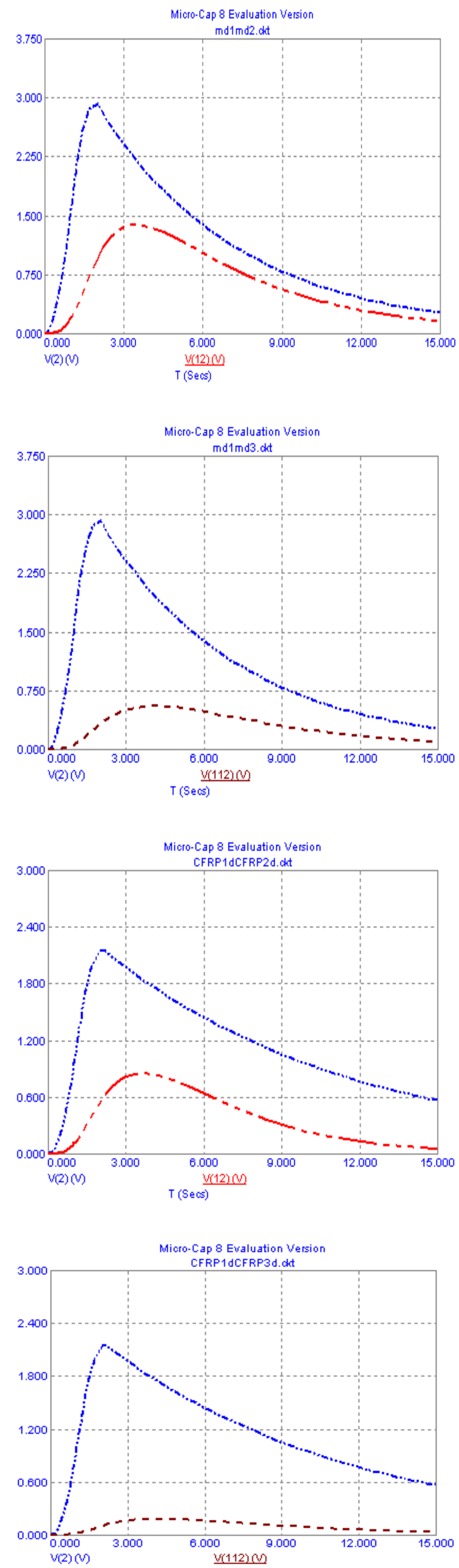

Fig. 5: 1D, 2D and 3D simulation results of mild steel (top two plots) and CFRP

The comparisons between 1D, 2D and 3D models based on simulated data highlights the prediction regarding thermal propagation (time) decay and amplitude decay with depth (Fig. 5). Here the anisotropy has not been invoked for CFRP. It may be pointed out at the outset of analysis and discussions that these comparisons do not bring out the relative merits of these models for predicting phase and group delay.

Figure 5 shows four graphs, of node voltages (temperature) versus time, for comparison of amplitude and time delay in mild steel and CFRP samples using 1D, 2D and 3D RC models. The node considered in all cases is the second node (into depth from surface).

The top two graphs pertain to mild-steel: the topmost comparing 1D and 2D evolution at the chosen nodes, and the next graph plotting 1D and 3D evolutions. The 1D plot is repeated in both for comparison.

The bottom two graphs show the simulated plots for the CFRP sample: the bottom most showing 1D and 3D model based response, while the graph above pertains to 1D and 2D. Again the 1D plot in both is repeated for reference and ease of comparison.

While comparing, two points need to be focused on: the peak amplitudes and the time at which they occur.

In general, the RC ladder network "branches/spreads out" as we go from 1D to 2D to 3D, i.e RC ladder combination increases. This accounts for the drop in peak amplitude as we go from 1D to 2D to 3D simulation for a given material sample, and is a consequence of the expected *lateral heat diffusion* which is also practically observed. On the time front, this results in comparatively less time being taken to propagate in 1D, little more in 2D and the most time in 3D.

7. Conclusions

Electro-thermal model based simulations have been carried out and comparisons made between 1D, 2D and 3D RC models. Decay in amplitude with depth as well as increase in peak propagation delay obtained from 1D, 2D and 3D results, are as per physical explanations and clearly show capability of the proposed models. The RC model has been extended with the addition of convection resistance and can also include effect of anisotropy.

8. References

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