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A normalization procedure for pulse thermographic nondestructive evaluation

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ABSTRACT

Pulse thermographic nondestructive evaluation (TNDE) technique can be used to estimate defect dimensions, and in particular the depth at which the defect is located. Numerical models of this procedure can aid in the interpretation of experimental results. However, the thermophysical properties of the test object as well as the amount of energy absorbed during this process are not readily available for such models. This paper presents an extension of the thermographic signal reconstruction (TSR) procedure in which the temperature and the time scales are respectively normalized with equilibrium temperature and the break time. In the normalized form these profiles are independent of material properties and instrumentation settings. Thus in the normalized format, experimental results can be readily compared with numerically generated thermographic results. The defect depth can also be easily obtained as a fraction of plate thickness from this plot.

1. Introduction

Thermographic nondestructive evaluation (TNDE) is one of the Nondestructive Evaluation (NDE) techniques capable of assessing large areas of structures in a relatively short duration of time [1]. In general TNDE can be classified into two main categories, namely active and passive thermographic techniques. In active thermography heat is applied to the surface of the test object by an external energy source while in passive thermography heat is generated within the object.

A comprehensive review on different thermographic techniques used in NDE and condition monitoring techniques is provided by Ibarra-Castanedo et al. [2] and Bagavathiappan et al. [3]. In addition to the pulsed thermography and lock-in thermography techniques newer approaches of exciting the specimens and extracting damage related information have been demonstrated by Gao et al. [4,5], and Ahmed et al. [6].

Pulse thermography falls under the category of active thermographic technique and it uses a pulse of heat energy applied to the surface of the test object, usually by a flash lamp. Following the instantaneous rise in the temperature of the surface, due to the applied heat, the rate of change of surface temperatures as a function of time is monitored using an infrared camera. In a defect free sample the heat diffuses through the thickness resulting in an asymptotic drop in surface temperature. However, in areas where there are defects, this diffusion of heat in the thickness direction is obstructed, and hence, the surface temperature remains higher than that of the defect free areas. Defect free areas in a plate are commonly termed as *sound zone* in the TNDE literature. The variation of temperature with time provides an indication of the depth at which the defect is located.

In TNDE field tests there are multiple unknowns that are to be quantified, namely, thermal diffusivity of the material, lateral dimension and depth of defects, thickness of the part being inspected, and amount of heat absorbed by the part from the flash. All of these parameters determine thermal images and their variation with time which are obtained from thermographic tests. As with other NDE techniques reliable calibration specimens would facilitate the characterization of defects. The existence of defects can be qualitatively seen in raw thermographic images. Quantitative information can be obtained with additional image processing techniques. There are two approaches in image processing, namely pixel based and image based techniques [7]. Pixel based technique is based on the temperature evolution of a single pixel or point on the surface. Shepard et al. [8] introduced a pixel based technique termed Thermographic Signal Reconstruction (TSR) technique. On the other hand, image based technique is based on spatial variations of temperature seen in the images at different instants of time. Both methods have their merits and it was noted by Shepard et al. [7] that combining both methods would also be of beneficial in quantitative characterization.

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This study uses pixel based approach for developing the normalization procedure. In these discussions, the variation of temperature with time recorded at an individual pixel is termed as the *thermographic profile* for that point. Normalization is widely used in presenting solutions to heat conduction problems. Fourier number is a fundamental parameter that characterizes transient heat conduction. Different reference values of temperature and time have been used in the past for normalizing thermographic profiles. Ringermacher et al. [9] used the time of occurrence of the maximum slope in the temperature versus time plot, the inflection time, as the reference parameter for normalization. The purpose of normalization in their study was to eliminate the influence of lateral heat flow when comparing thermographic profiles of different defects. Krishnapillai et al. [10] numerically generated thermographic profiles of defects in composite laminates and these results were validated through suitable experiments. They used the inflection time to find a calibration value for diffusivity to correlate experimental and numerical results. Ramirez-Granados et al. [11] carried out a normalization procedure in which the time and temperature difference were normalized with respect to the maximum values, in order to validate their approach and to aid better comparisons of the results for a variety of specimens. Balageas [12] provided a detailed assessment of different approaches for extracting quantitative information from thermographic nondestructive tests, and pointed out a few of the current deficiencies. He also introduced a procedure for minimizing variations in intensity of images that are caused by variation in the absorption of incident radiation. He used the temperatures of the pixels at a time immediately following the flash, such as 0.1 s after the flash, to normalize the temperature.

The objective of this research is to provide a better means of comparing and correlating thermographic results from numerical and experimental analyses. There are some challenges in quantitative matching of experimental results with results from numerical simulations. The first difficulty arises from the fact that accurate thermo-mechanical properties of the specimen under investigation are not generally available prior to the test. The second difficulty arises from the fact that the temperature values obtained in the experiments cannot be readily related to those in the numerical simulations, because of the arbitrary, but linear scale variation of signal received from the thermographic camera. A new normalization scheme is introduced in this research that eliminates both of these difficulties. Further, as a result of this normalization, it is feasible to directly obtain estimation of defect depth as a fraction of plate thickness. As shown in later sections, results from a validated numerical simulation can be used to generate thermographic profiles corresponding to a range of materials and flash intensities as long as the defect geometry remains the same. Once the numerical simulations are validated, it becomes readily feasible to create a database of thermographic profiles that can help in the interpretation of results obtained in the field.

2. Theoretical background

The variation of surface temperature of a semi-infinite solid as a function of time, after the surface is subjected to an instantaneous rise in temperature such as in flash heating, is given by [13],

$$\Delta T = \frac{q_0}{\varepsilon\sqrt{\pi t}} \tag{1}$$

where $\Delta T = T - T_0$, which is the difference between the temperature T at any time t after the flash and the initial temperature T_0 of the surface before the flash, q_0 is the heat supplied at the boundary as a flash and ε is the effusivity given by,

$$\varepsilon = \sqrt{\kappa\rho c}. \tag{2}$$

In Eq. (2), κ, ρ, and c are thermal conductivity, density, and heat capacity of the material respectively. In a semi-infinite body, following the flash, the surface temperature instantaneously raises and subsequently decreases according to the relationship given in Eq. (1). However, for a slab with a finite thickness of L, the evolution of ΔT can be derived from the equations given in [13] and is given as,

$$\Delta T = \frac{q_0}{L\rho c}\left\{1 + 2\sum_{i=1}^{\infty} e^{\left(-\pi^2 i^2 \frac{\alpha t}{L^2}\right)}\right\} \tag{3}$$

where α is the diffusivity of the material given by,

$$\alpha = \frac{\kappa}{\rho c} \tag{4}$$

The equilibrium temperature or saturation temperature difference, when the temperature of the plate (slab) becomes uniform throughout its thickness, is given by,

$$\Delta T^* = \frac{q_0}{L\rho c} \tag{5}$$

Using Eqs. (1) and (5), the corresponding time at which saturation occurs, commonly referred to as break time, t^*, is given by,

$$t^* = \frac{L^2}{\pi\alpha} \tag{6}$$

This equation is often used to find the thermal diffusivity of materials using flash thermographic technique [14]. Taking natural logarithm of Eq. (1) results in the following equation,

$$\ln(\Delta T) = -0.5\ln(t) + \ln\left\{\frac{q_0}{\varepsilon\sqrt{\pi}}\right\} \tag{7}$$

For the semi-infinite body, the slope of the plot of $\ln\Delta T$ versus $\ln(t)$ has a value of -0.5. However, for a finite thickness plate, as indicated in Eq. (3), the temperature difference will eventually levels off to a value of ΔT^*. The variation of ΔT as a function of time in logarithmic domain is shown in Fig. 1 for both the semi-infinite body as well as a finite thickness plate. It has been found that the plots of first and second derivatives of the $\ln(\Delta T)$ with respect to $\ln(t)$ are quite informative as demonstrated by Shepard et al. [8]. These are referred to as the first derivative and the second derivative, or $1d$ and $2d$ by Shepard and they are given by (Fig. 2)

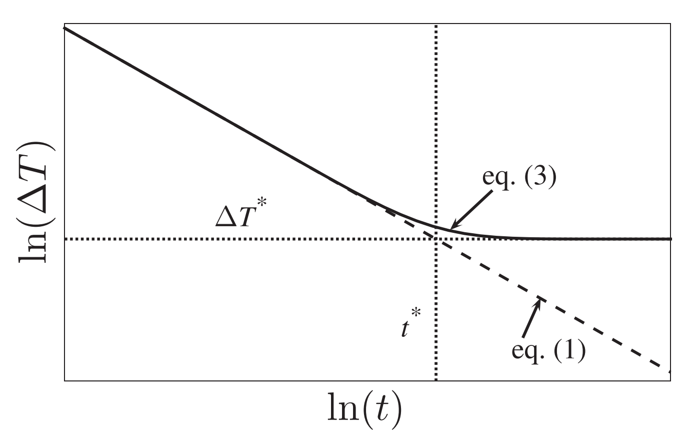

Fig. 1. Schematic variation of $\ln(\Delta T)$ with $\ln(t)$.