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Rectification of depth measurement using pulsed thermography with logarithmic peak second derivative method

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HIGHLIGHTS

- It is widely accept that the traditional depth prediction method of logarithmic peak second derivative (LPSD) based on one-dimensional heat transfer model is independent of defect size or defect aspect ratio (diameter/depth). In this paper, analytical model and experimental results were in good agreement and both revealed the same thing that LPSD method was affected by the defect size or aspect ratio.
- We constructed the relation between the specific characteristic time (SCT) of LPSD method and defect aspect ratio when considering the defect size. This relation was verified by GFRP and stainless steel samples and it is independent of defect depth and material.
- We proposed an improved LPSD method for depth prediction, and the estimation of defect size had small influence on the accuracy for depth calculation.

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ABSTRACT

Logarithmic peak second derivative (LPSD) method is the most popular method for depth prediction in pulsed thermography. It is widely accepted that this method is independent of defect size. The theoretical model for LPSD method is based on the one-dimensional solution of heat conduction without considering the effect of defect size. When a decay term considering defect aspect ratio is introduced into the solution to correct the three-dimensional thermal diffusion effect, we found that LPSD method is affected by defect size by analytical model. Furthermore, we constructed the relation between the characteristic time of LPSD method and defect aspect ratio, which was verified with the experimental results of stainless steel and glass fiber reinforced plate (GFRP) samples. We also proposed an improved LPSD method for depth prediction when the effect of defect size was considered, and the rectification results of stainless steel and GFRP samples were presented and discussed.

1. Introduction

Pulsed thermography is one of the most promising nondestructive evaluation (NDE) techniques for the reason that it is non-contact, wide span of application, large area for one shot, single side-access and curvature tolerant, etc. [1]. This technique is proven to be a good method both in the qualitative and quantitative evaluation. Many qualitative applications have been reported, such as adhesion failure, delamination defects, impact damage, liquid ingress recognition, corrosion and so on [2–5].

Several depth prediction methods were reported in the literature. To begin with, depth prediction process featured as finding a specific characteristic time (SCT) in the temperature decay and correlated SCT with the depth. This kind of method is most commonly used. For example, peak contrast time (PCT) method [6–7], peak slope time (PST) method [8–10], half-rise time method [11], half-rise contrast time method [12], early-time method [13–14], absolute peak slope time (APST) method [15], deviation time method [16], logarithmic first derivative half-rise time method [17] and logarithmic peak second derivative time method (LPSD) [18]. Secondly, X. Maldague developed a pulsed phase thermography (PPT) method [19] and used a blind frequency method to predict depth [20–21]. Besides, the related lock-in thermography also uses phase angle measurements to predict underlying defects [22]. There are many other depth prediction methods, including least-squares fitting method, neural network and tomography. Sun developed a least-squares fitting method which utilizes a

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theoretical heat transfer model to fit the test data and predict depth accordingly [23]. It is also reported that evaluating the defect depth uses neural network [24–25]. Thermal tomography method can also be used as a depth prediction method which can visualize the depth from cross-sectional slice image if a special dimension has been known in the field of view [26].

All methods mentioned above using SCT to predict depth are based on the solutions of one-dimensional heat conduction model either for semi-infinite body or a solid plate, which does not consider the effect of three-dimensional heat conduction. Currently, it is generally accepted that PCT method is affected by defect size, and LPSD method is not [6–10]. In order to investigate how defect size affects SCT of PCT method, D.P. Almond developed a method that introducing a decay term considering defect aspect ratio (defect diameter/defect depth) in the solution for the semi-infinite body [27].

In this study, LPSD method will be investigated if it is affected by defect size when the decay term considering defect aspect ratio is introduced in the solution of heat conduction. The samples of GFRP and stainless steel (SS) materials are manufactured with many flat bottom holes of different defect aspect ratios and used for an experimental demonstration.

2. Theory

In reflective pulsed thermography, the temperature of the front surface of the sample rises instantaneously under the thermal excitation with a short pulse of light, and then the temperature decreases and tends to heat balance. An infrared camera is employed to capture the surface temperature variation process on the same side. Surface temperature T above a thermal discontinuity with time t is normally expressed with two equations in pulsed thermographic applications. One is the solution of the Fourier equation for the adiabatic heating of a solid plate by an instantaneous pulse [7]:

$$T(t) = \frac{q}{\rho C d}\left[1 + 2\sum_{n=1}^{\infty}\exp\left(\frac{-n^2\pi^2\alpha t}{d^2}\right)\right] \quad (1)$$

where q (W/m^2) is the input energy per unit area, d is defect depth, α (m^2/s) is thermal diffusivity, ρ (kg/m^3) is density and C (J/kg·K) is specific heat. The other is the solution of the Fourier equation for the adiabatic heating of a thermally thick specimen by an instantaneous pulse:

$$T(t) = \frac{q}{e\sqrt{\pi t}}\left[1 + 2\sum_{n=1}^{\infty}R^n\exp\left(\frac{-n^2 d^2}{\alpha t}\right)\right] \quad (2)$$

where e ($\mathrm{W}\cdot\sqrt{\mathrm{s}}\cdot\mathrm{m}^{-2}\cdot K^{-1}$) is thermal effusivity, $R = \frac{e_1 - e_2}{e_1 + e_2}$ is the thermal reflection coefficient which could be assumed to be 1 for solid-air interface [26].

The second derivative curve of the analytical temperature with Eq. (1) in logarithmic scale has one maximal peak, which is the SCT of LPSD method [6]:

$$t_r = \frac{d^2}{\pi\alpha} \quad (3)$$

For the defects with the same depth and different size, the maximal peak has the same SCT as shown in Eq. (3). In Eq. (1) and Eq. (2), there is no term concerned about defect size, and the SCT shown in Eq. (3) is relatively early which leads to the thought that it is not affected by three-dimensional heat conduction, and it is also verified by some applications. Therefore, it is widely accepted that LPSD method is independent of defect size.

In order to evaluate the effect of a circular defect with a diameter D at a depth d on temperature decay, a decay term $\left(1 - e^{-\frac{(D/2)^2}{4\alpha t}}\right)$ is introduced in Eq. (2), considering the heat diffusion from the defect center of circular to the edge at a distance $D/2$ away. So Eq. (2) can be expressed as [27]:

$$\mathrm{T(t)} = \frac{q}{e\sqrt{\pi t}}\left[1 + 2\sum_{n=1}^{\infty}R^n\exp\left(\frac{-n^2 d^2}{\alpha t}\right)\left(1 - e^{-\frac{(pd)^2}{16\alpha t}}\right)\right] \quad (4)$$

where p is defect aspect ratio and equals to D/d. Once the decay term considering the defect size is concerned, the surface temperature decay is certainly affected accordingly. The temperature decay in logarithmic scale simulated with Eq. (4) is shown in Fig. 1, in which R is set to 1, d is 2 mm, α is 4.595×10^{-6} m^2/s (stainless steel), and p is chosen as integer numbers from 1 to 10. Fig. 1 shows that the temperature curve with a bigger p at the same depth drops slower because it has a bigger defect area and can trap more heat which has a longer distance for the lateral heat diffusion to the surrounding cooler and sound area. According to Eq. (4), when p is very big, the corresponding temperature curve is more close to the temperature curve without considering the defect size; and when p is very small, for example 1, its temperature curve is more close to the reference temperature curve.

In order to investigate if LPSD method is affected by the defect size, the second derivative of temperature decay in logarithmic scale is:

$$\frac{\mathrm{d^2(lnT)}}{\mathrm{d(lnt)^2}} = \frac{\mathrm{t}}{\mathrm{T}}\frac{\mathrm{dT}}{\mathrm{dt}} - \frac{\mathrm{t^2}}{\mathrm{T^2}}\left(\frac{\mathrm{dT}}{\mathrm{dt}}\right)^2 + \frac{\mathrm{t^2}}{\mathrm{T}}\frac{\mathrm{d^2T}}{\mathrm{dt^2}} \quad (5)$$

where the first and second derivative of temperature T over time t can be obtained from Eq. (4), however, too many terms are involved and the SCT need to be obtained [27]. In this study, the second derivative curves are obtained by directly applying the second derivative on the data shown in Fig. 1, and the results are plotted in Fig. 2. Fig. 2 clearly shows that the peak values and times are affected by defect size or defect aspect ratio. For both the maximal and minimal peaks, LPSD curve with a smaller p has a smaller peak time and amplitude. However, the maximal peak almost does not change when p is bigger than 7, and the minimal peak still changes a lot when p equals to 10, which means that the maximal peak is less affected by defect size.

In order to investigate how defect size affects the SCT of LPSD method, the same analytical methods were applied for different defect depths and materials including stainless steel (whose thermal diffusivity is 4.595×10^{-6} m^2/s) and GFRP (whose thermal diffusivity is 3.4×10^{-7} m^2/s), and all the maximal peak times t_{LPSD}

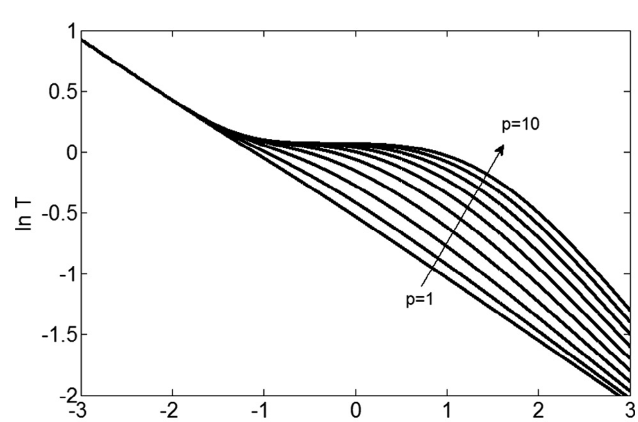

Fig. 1. Temperature decays of simulated defects using Eq. (4) in stainless steel (SS) which have the same depth (2 mm) and different p (defect aspect ratio) range from 1 to 10.