Infrared Physics & Technology 72 (2015) 204–209

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Delamination detection in glass–epoxy composites using step-phase thermography (SPT)

K. Ghadermazi, M.A. Khozeimeh, F. Taheri-Behrooz, M.S. Safizadeh *

School of Mechanical Engineering, Iran University of Science and Technology, Narmak, Tehran 1674613114, Iran

HIGHLIGHTS

- Delamination detection in Glass/epoxy composites by using step heating thermography technique.
- Fourier transform application to raw thermography data to detect defects in composites.
- FE simulation of thermography process, to find the optimum of the test parameters as heating power and time step.
- The present technique improved not only the signal-to-noise ratio of the defect signatures, but the edge sharpness as well.

ARTICLE INFO

Article history:
Received 15 March 2015
Available online 8 August 2015

Keywords:
Step heating thermography
Glass epoxy composite
Delamination defect
Fourier transform
Finite element modeling

ABSTRACT

Inspection of Glass/epoxy composite using infrared has always been a challenge. This paper presents the use of step heating thermography to increase the maximum detectable defect depth. Fourier transform is applied to step heating data to obtain phase images. These images use to quantitatively characterize defect depth and dimensions in composites. Desired parameters of step heating test such as time step and heating rate are obtained from finite element modeling of composites. This model provides an estimation of defect depth thermal resistance from early time surface temperature. Therefore, it is possible to predict the best frame in an infrared video. Experimental results show the improvement of defect detectability by step heating thermography.

1. Introduction

Many researches have been done on composites for evaluating their integrity and operation during their useful life. For many years Infrared thermography has been presented as an NDT technique that having great potential for rapid scanning of large surface areas and also it can be applied some distance away from the test surface [1–7].

Probably pulse thermography is the most commonly used heating method, while it may not be appropriate for thick composites. As composites are low conductive materials, intense pulses may be needed for thick specimens. However, pulses must be limited to avoid damaging the structure [8]. While Lock – in thermography provides more temperature rise than other conventional thermography techniques, it needs more time to identify small defects. Another disadvantages of lock – in thermography is that it needs more sophisticated stimulation source and data acquisition apparatus [5,11,12]. Step heating thermography using a long pulse of low power heat excitation, gets over some of the limitations of pulse thermography. Furthermore Step heating thermography provides more temperature contrast than pulsed thermography. Since this technique runs on the low heat power, it allows a longer heating time to identify deeper defects with no damaging to the sample [9,10].

Many researches have been done on pulsed and step heating thermography for defect detection [12–17]. Although raw data from pulsed and step heating thermography are used for primary detection but the post processing of raw data is necessary to increase temperature contrast and to improve detection of small size and deeper defects. Many processing techniques to enhance the contrast of the raw data have been developed [18–24].

In comparison to pulsed thermography, relatively less past research has been performed for step heating thermography. Many of researches that have been done for step heating thermography focused on investigating thin coating. According to [25] step heating thermography is suitable for impact damage inspection in composite materials. Almost in all previous works that has been done on step heating thermography just the raw data have been analyzed. Recently, the Thermographic Signal Reconstruction

* Corresponding author.
E-mail address: safizadeh@iust.ac.ir (M.S. Safizadeh).

http://dx.doi.org/10.1016/j.infrared.2015.08.006
1350-4495/

(TSR) and the early detection/characterization methods have been applied to step heating thermography with very good results. Daniel has showed that the Thermographic Signal Reconstruction (TSR) and the early detection post processing techniques which commonly used for pulsed thermography can be applied on step heating thermography raw data [26,27]. Application of Fourier Transform on pulsed thermography raw data introduced pulsed phase thermography technique which allows to analyze the experimental data in frequency domain.

The present paper shows how the phase of Fourier transform of step heating thermography raw data can been obtained. Delamination type defects are detected experimentally on Glass/epoxy composites by employing step heating thermography. Commercial finite element software Abaqus was employed to simulate thermography process in composite laminates with the flaws. Capability of numerical methods to detect flaws with different flaw sizes and heating power are investigated.

2. Theory

The 1-D Heat diffusion for the case of step heating illustrated in Fig. 1. A heat flux is uniformly applied to the front surface, and for the back surface adiabatic boundary condition is assumed. The temperature rise through the thickness was identified by Eq. (1) [28].

$$T(X,t) = \frac{2\sqrt{\alpha t}Q}{k}\sum_{n=0}^{\infty}\left[ierfc\frac{L(1+2n)-X}{2\sqrt{\alpha t}} + ierfc\frac{L(1+2n)+X}{2\sqrt{\alpha t}}\right] \quad (1)$$

where T is the temperature, t is the time and α and k are the thermal diffusivity and thermal conductivity, respectively. L is the plate thickness and Q is the heat flux.

The surface temperature is obtained by substituting $X = L$ into Eq. (1):

$$T(L,t) = \frac{2\sqrt{\alpha t}Q}{k\sqrt{\pi}}\left[1+\sqrt{\pi}\sum_{n=1}^{\infty}2ierfc\frac{nL}{\sqrt{\alpha t}}\right] \quad (2)$$

In Eqs. (1) and (2) $ierfc$ is the first integral of the complementary error function and defined as:

$$ierfc(\xi) = \frac{1}{\sqrt{\pi}}e^{-\xi^2} - \xi ierfc(\xi) \quad (3)$$

Worth to mention that for Glass/epoxy composites the thermal diffusivity is low so the integral of the complimentary error function argument is large and $ierfc$ approaches to zero:

$$T = \frac{2Q}{k}\left(\frac{\alpha t}{\pi}\right)^{1/2} \quad (4)$$

Eq. (4) shows that the temperature rise in sound area (non-defected pixels) is linearly related to the square of the time. For the defected pixels temperature rise deviated from non- defected pixels. This difference between the two responses of non- defected and defected areas is used to applying the Fourier change transforming procedure.

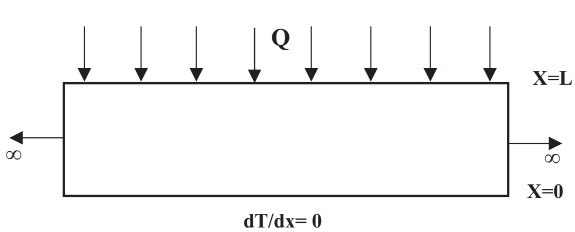

Fig. 1. One-dimensional step heating of heat conduction problem.

Fourier transform is an interesting processing technique in which data is transformed from time domain to frequency domain. The one- dimensional discrete Fourier transform (DFT) is defined as Eq. (5) [9]:

$$F = \Delta t\sum_{k=0}^{N-1}T(k\Delta t)exp^{-j2\pi nk/N} = Re_n + Im_n \quad (5)$$

where j is the imaginary number ($j^2 = -1$), n determine the frequency increment ($n = 0, 1\ldots N$), Re and Im are the real and the imaginary terms of the transform, respectively and Δt is the sampling period.

Amplitude A, and the phase $\varnothing$ are estimated using real and imaginary parts of the complex transform as Eq. (6) [9]:

$$A_n = \sqrt{Re_n^2 + Im_n^2} \; and \; \varnothing_n = \tan^{-1}\left(\frac{Re_n}{Im_n}\right) \quad (6)$$

The phase is of particular attention in NDE since that it is less affected than raw data by environmental reflections, non-uniform heating, emissivity variations and area geometry. Using the phase image obtained from raw data of step heating thermography defect detection is investigated.

3. Finite element modeling

Temperature transfer formula is hardly solved when using the analytical solution because of complicated construction of specimen, non-linearization boundary and anisotropic thermo-physical properties of Glass/epoxy composites. Many of researchers have tried to solve the heat transfer problems (conduction and radiation) in the composite materials. For example, heat transfer in the anisotropic multi-layers composite materials were investigated for some limited cases without considering defect by [29–34].

Recent methods about defect size and depth estimation tend to be for isotropic materials and for the assumption of 1D heat conduction. In the most cases of finite-sized defects, the heat flow interaction with defects is more than one-dimension. Extra dilemma exists when it comes to composites with different energy properties in various directions. Simple 1D heat conduction structured models are unqualified to help accurately predict heat conduction about defects, hence the actual estimation of defect size and depth is often not accurate. In this study, finite element modeling was employed to simulate the heat transfer phenomena inside the Glass/epoxy laminates with embedded defects as delamination. For this purpose the commercially FE software Abaqus was used to simulate composite plates in 3-dimension. Defects are simulated in FE models by using different thickness of Teflon materials.

The well-known basic Fourier relation of heat transfer by conduction for an isotropic material is given by Eq. (7). where q_n is the rate of heat flow per unit area normal to the direction n, Q_n is the rate of heat flow across the area A_n normal to the direction n, k is the normal conductivity of material. Physical and thermal properties of materials are tabulated in Table 2.

$$Q_n = \frac{q_n}{A} = -k_{ij}\times\frac{\partial T}{\partial t} \quad (7)$$

Table 1
Physical and thermal properties of materials [35].

Thermophysical properties					
Material	K (W/m c)			C (J/kg c)	ρ (kg/m^3)
Glass/epoxy	k_x 1.5	k_y 1.5	k_z 1	840	1900
Teflon	0.25			1172	2170