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Test method

A novel approach for one-sided thermal nondestructive testing of composites by using infrared thermography

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ABSTRACT

One-sided thermal non-destructive testing (TNDT) is of vital importance in aerospace composites to monitor structural degradation, as well as to detect subsurface defects. The objective of this study is to evaluate simultaneously the thermal diffusivity and to characterize the defects within carbon fiber reinforced polymer (CFRP) composites. In this paper, a novel one sided TNDT technique is presented which relies on creating an artificial inflection point by multiplying front-surface temperature evolution by n^{th} power of time, where $0 < n < 0.5$, followed by optimization of n. An analytical solution of the diffusivity calculation and defect characterization in the case of CFRP composite plate is discussed. The characterization of low velocity impact damage is also investigated with the help of theoretical and experimental results. Some key research points which need further exploration are also discussed.

1. Introduction

The term “Thermal Nondestructive Testing” (TNDT) encompasses two fairly different areas of research. The first area is concerned with the analysis of material thermal properties by solving a particular problem of heat conduction, resulting in the determination of material thermal conductivity K, heat capacity C and thermal diffusivity $a = K/C\rho$, where ρ is the material density. Research in this area is typically more emphasized on the determination of diffusivity [1,2] as it is considered as the most important parameter responsible for transient thermal events. The second research area deals with evaluation of structural macro-defects such as voids, cracks, disbonds, inclusions, delaminations etc. [3–5]. There is an evident bridge between these two areas, in particular, when agglomerations of micro-defects (pores, fiber micro-breaks, etc.) change integral thermal properties or the presence of macro-defects leads to local variations of material thermal properties. Infrared (IR) thermography may serve as an express tool for evaluating material thermal properties in a one-sided, or front-surface, procedure where both an infrared imager and a heater are positioned on the same side of a tested object.

Due to deep physical reasons, front-surface procedures are less sensitive to both diffusivity variations [6] and defect presence [7]. Despite these factors, one-sided inspection is more interesting in practice because of its applicability to situations where two-sided procedures cannot be applied due to non-accessibility of the rear surface. Typically, a test procedure is reduced to the processing of a front-surface temperature response after/within periodical, flash or step-wise thermal stimulation. Normally, the corresponding response curves contain no characteristic (inflection) time points, therefore, one should artificially introduce a reference point when processing test results. Periodic, or thermal wave stimulation can be traced to the earlier works of Rosenzweig and Gersho [8], Busse et al. [9], Mandelis et al. [10] and other researchers. In the last decade, this technique is thermographically realized as

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a lock-in TNDT [10]. Peculiarities of the pulsed technique were recently summarized by Balageas and Roche [11]. There is a long-lasting discussion on which stimulation technique – periodic or flash – is more efficient. We believe that both techniques, when properly optimized, produce close results. In this study, we introduce a novel processing technique which can be applied to the characterization of both thermal properties and hidden defects in a one-sided test procedure. The potential of this novel technique for characterizing low velocity impact damage in CFRP composite is also investigated.

2. Test model

The basic model to be analyzed is a 'classical' plate-like sample (Fig. 1a) stimulated with a heat flux which ensures the absorbed power density Q and operates during time τ_h (heat pulse duration). The temperature responses on both front (F) and rear (R) surface of the sample are analyzed at a characteristic heat transit time τ^*. If $\tau^* >> \tau_h$, the heating can be considered as Dirac-like, or flash. This case will be discussed below, while the case of $\tau^* \sim \tau_h$ needs further exploration, although one may expect no considerable difference between the two cases [11]. There is convective heat exchange between the sample and the ambient characterized by the coefficient h. However, the sample can be regarded as adiabatic if $hL/K < 0.1$, where L is the sample thickness. The sample in Fig. 1a contains a void-like defect at a depth l having lateral size $S_{x,y}$ and thickness d. The mathematical formulation of the problem above is trivial [12].

Fig. 1b shows the temperature responses in the inspection of a 2 mm-thick CFRP sample heated with a heat pulse ($Q = 10^6$ Wm^{-2}, $\tau_h = 0.01$ s). The solutions are obtained by analytically solving a three-layer non-adiabatic problem [13]. Three test cases are considered: a non-defect plate ($a = 3.15 \times 10^{-7}$ m^2/s, $K = 0.57$ Wm^{-1}K^{-1}, $h = 10$ Wm^{-2}K^{-1}), a non-defect plate with both a and K values being increased by 25% and an infinite ($S_{x,y} = \infty$) air-filled defect of thickness 0.1 mm ($a = 5.8 \times 10^{-5}$ m^{2}s^{-1}, $K = 0.07$ Wm^{-1}K^{-1}) at a depth of 0.5 mm.

The conclusions drawn from this test model including differences between front and rear side temperature profiles will be discussed in section 3.

3. Determining diffusivity of a non-defective material

Over the last four decades, photothermal and photoacoustic [2,14] techniques have been mainly used for the thermal diffusivity measurement. Nowadays, a type of photothermal technique termed 'laser flash method' [15,16] is often regarded as a standard method for determining thermal diffusivity of solid materials. Due to advancements in infrared (IR) technology and electronics, insitu thermal diffusivity evaluation has become possible unlike solely laboratory applications of the original photothermal technique. Such measurements are necessary in many applications of critical concern, for example, in the inspection of aerospace composites, where one has to monitor structural degradation of material, as well as to detect hidden defects.

The temperature on the plate rear surface as a function of time is calculated by using the analytical solution for heat conduction in an infinite plate of thickness L, conductivity K and diffusivity a uniformly heated on the front surface by a Dirac pulse:

$$T = \frac{Wa}{KL}\left(1 + 2\sum_{n=1}^{\infty}(-1)^n e^{-n^2\pi^2 Fo}\right), \tag{1}$$

where W is the Dirac pulse energy (in real cases $W = Q\tau_h$), $F_0 = a\tau/L^2$ is the Fourier number.

Due to the term -1^n, Eq. (1) predicts that the rear-surface temperature increases monotonically because of alternate signs of the series terms. In the aerospace industry, materials evaluation is mostly restricted to the reflection mode of pulsed thermographic NDT because of non-accessibility of the rear surface for the inspection. This situation makes it interesting to analyze the possibility of determining diffusivity in the reflection mode. For a heated front side, the corresponding solution is the same as given by Eq. (1), excluding the term -1^n. This

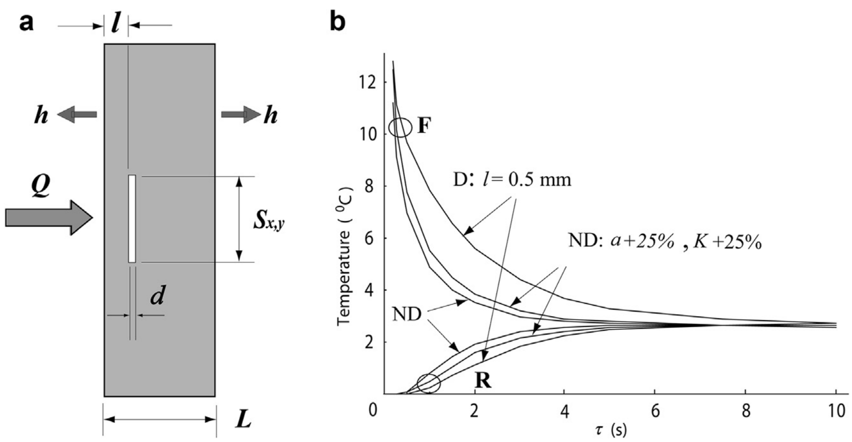

Fig. 1. Basic TNDT model: (a) schematic test model, and (b) front- and rear-surface temperature responses for CFRP specimen in three different test cases.