

1.5.1. INFRARED THERMOGRAPHIC NONDESTRUCTIVE TESTING OF COMPOSITE MATERIALS: DETERMINING THERMAL PROPERTIES, DETECTING AND CHARACTERIZING HIDDEN DEFECTS

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Due to permanent improvement of thermal resolution and imaging speed of infrared (IR) imagers, the last decade has been characterized by growing applications of IR thermographic non-destructive testing (IR TNDT) in the inspection of metals. However, non-metals, particularly, composite materials and honeycombs are still considered as the most successful objects for applying TNDT techniques. First of all, this is explained by the difficulties which are met when applying 'traditional' NDT methods to these materials.

In this paper, a closed-up approach to IR TNDT of composite structures is presented, including the determination of thermal properties, defect detection and characterization of defect parameters. The discussed experimental results have been mainly obtained on graphite/epoxy composites, which are widely used on aero space and other areas, by using the IR TNDT software package developed by Innovation Inc. (Russia).

The knowledge of composite thermal properties is necessary when determining defect detection limits and, particularly, when characterizing defects. The classical thermal properties of materials are the thermal conductivity λ , the heat capacity C and the density ρ . If temperature of composites may sharply change, the two last parameters are typically replaced with the thermal diffusivity $a = \lambda / C\rho$. It is important that, in the case of composites, both parameters λ and a can be significantly anisotropic, i.e. one should take into account their corresponding spatial components, such as a_x , a_y , a_z .

A transverse (through-the-thickness) component a_z is typically determined by applying the Parker's (flash) technique. When using IR thermography in the inspection of 'thick' (up to 15 mm-thick) composites, there are two points of interest: 1) the conversion of standard IR images into images of diffusivity distributions, and 2) the necessity of applying square pulse, rather than flash, heating and taking into account some additional factors, in particular, surface heat exchange and lateral diffusion phenomena. In our study, all these parameters can be introduced into consideration by using the ThermoCalc-6L modeling program. Determining a_z is illustrated by fig. 1.

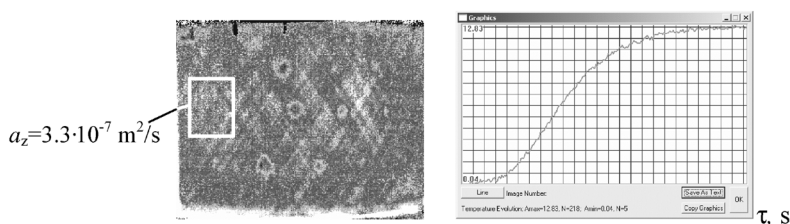


Fig. 1. Determining thermal diffusivity of a conical graphite/epoxy composite sample by applying IR TNDT (left – IR image, square area for averaging a_z ; right – Parker's temperature response used for calculating a_z)

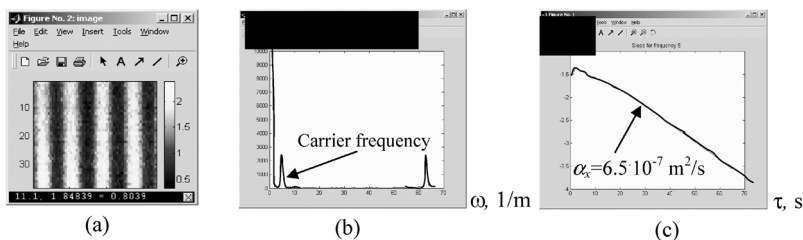


Fig. 2. Determining diffusivity lateral components of a graphite/epoxy composite:

- (a) – slit heat mask; (b) – Fourier spectrum clearly showing the carrier frequency;
 (c) – logarithmic temperature evolution curve at the carrier frequency,
 of which slope is numerically equal to α_x

A rather new area of academic and applied interest is the determination of diffusivity lateral components α_x , α_y . The appropriate technique is based on using the 2D Fourier transform applied to surface temperature distributions. This technique can be implemented in both one- and two-sided IR TNDT procedures being independent on material semi-transparency and surface heat exchange. The problem can be simulated by using the ThermoCalc-30L program which allows modeling a composite which consists of up to 30 layers (plies) arbitrarily tilted in regard each to other. The main problem to solve when applying the Fourier transform technique is choosing an optimum spatial frequency for calculating α_x , α_y . Our most trust-worthy results have been obtained by using a slit-mask technique which, unlike arbitrary heating, allows the easy choice of a proper carrier spatial frequency. The steps of the slit-mask procedure are shown in fig. 2.

Since thermal properties of materials are determined, defect detection limits can be evaluated by comparing significant detection parameters, such as temperature signals and contrasts, and experimental estimates of noise adherent to particular materials. In application to graphite/epoxy composites, the IR TNDT detection limits can be evaluated by applying the following rules: 1) surface temperature must not exceed 100°C , 2) temperature signals over defects must exceed temperature resolution of used IR imagers, and 3) temperature contrasts must be higher than 2 – 4 % that is a threshold noise value for graphite epoxy composites. The example of a defect map obtained at particular statistical decision-making parameters is given in fig. 3.

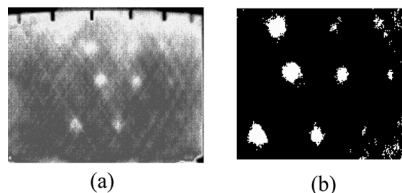


Fig. 3. Two-sided IR TNDT of a 15 mm – thick graphite/epoxy composite by applying 10 s heating:

- (a) – optimal source image; (b) – map of defects compiled by phasegram
 (correct detection $P_{c.d.} = 100\%$, false alarm $P_{f.a.} = 10\%$)

Defect characterization represents the most difficult task. First of all, mathematically, it is a fascinating area of research intended for solving ill-posed problems. Unfortunately, many available theoretical algorithms are labor- and time-consuming and can be hardly used in practice. More simple solutions involve analytical formulas which arrive from 1D solutions to classical heat conduction problems or represent a type of approximations of 2D and 3D solutions obtained numerically. The last approach is implemented in the ThermoFit Pro software intended for processing IR image sequences. A unique defect characterization option available in ThermoFit Pro allows the evaluation of defect lateral size, depth and thickness. The potentials and limits of this procedure are discussed in the paper.

The main conclusion which follows our research is that both the commercially-available IR imagers and the modeling/processing software are matured enough to allow the design and practical implementation of TNDT devices intended for the inspection of composite materials.