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

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1. Introduction

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 nondestructive testing (IR TNDT) in the inspection of metals. However, non-metals, particularly, composite materials and honeycombs, are still considered as the most successful targets for the application of TNDT procedures. First of all, this is explained by difficulties which one meets when applying 'traditional' NDT methods to the inspection of these materials.

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

2. Typical TNDT procedures

Typical procedures of active TNDT are presented in Fig. 1 (experimental set-ups used at Tomsk Polytechnic University).

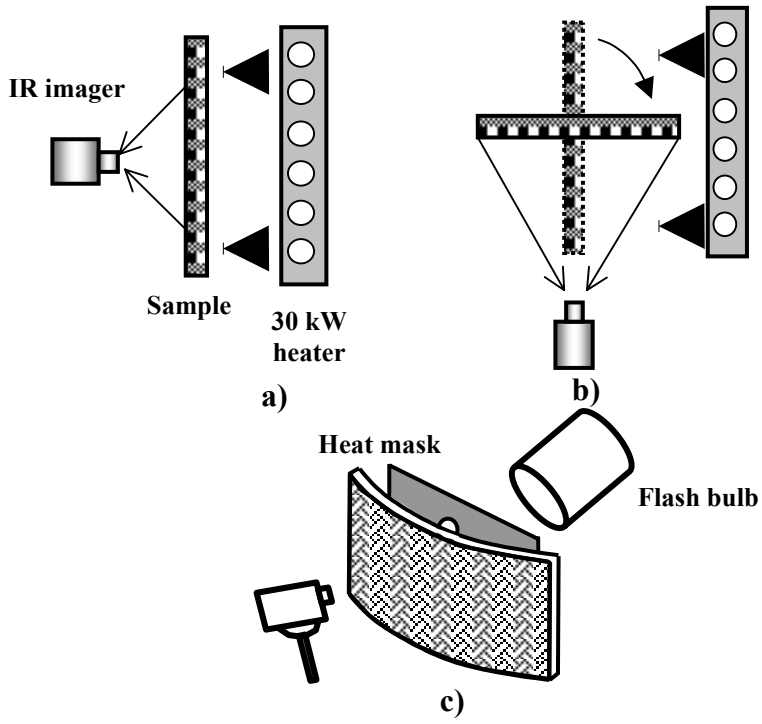


Fig. 1. Active TNDT schemes:

a – two-sided test,
b – one-sided test,
c – two-sided test, heat mask

It is believed that the most sensitive to hidden defects is the two-sided procedure (Fig. 1a). A sample is heated by a powerful (up to 30 kW) optical heater which can be realized on the basis of halogen tubular lamps. An IR imager monitors the rear surface of samples under test. Of course,

very thick and/or low-conductive materials cannot be inspected in such procedure due to low temperature signals on the rear surface and a danger of over-heating on the front surface.
One-sided TNDT is preferable when detecting defects located close to a tested surface. As shown in Fig. 1b, a sample is heated in front of a heater and then tilted by 90^o to perform temperature recording (in this way one will avoid spurious reflected radiation in the cooling stage).
Thermal properties of materials are typically determined in a two-sided procedure by placing a heat mask between the sample and the heater (Fig. 1c). By means of the IR imager, one records dynamic temperature distributions on the sample surface heated through the mask. The temperature pattern depends on anisotropic thermal properties of the material.

3. Determining thermal properties

In TNDT, the knowledge of composite thermal properties is necessary when determining defect detection limits and characterizing defects. In general, thermal properties determine material endurance toward extreme thermal loading that is of a particular interest in aero space.
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, thus being characterized by their corresponding spatial components, such as a_x, a_y, a_z. A grade of anisotropy depends on raw component properties and manufacturing technology. In the case of graphite/epoxy composites, the fiber lay-out and the number of plies influence the integral thermal conductivity and diffusivity.
A transverse (through-the-thickness) component a_z is typically determined by applying the classical Parker's (flash) technique. When applying this technique for the analysis of 'thick' (up to 15 mm) 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 three-dimensional (3D) modeling program [1,2]. Determining a_z by using a modified Parker's method is illustrated by Fig. 2. The proposed procedure requires the acquisition of image sequences which reflects a temperature build-up on the rear surface of samples (see Fig. 2, right). The temperature profile can be averaged in an area considered sound, because hidden defects may seriously distort a true value of material diffusivity. Such temperature profiles allow synthesizing images of thermal diffusivity (Fig. 2, left)

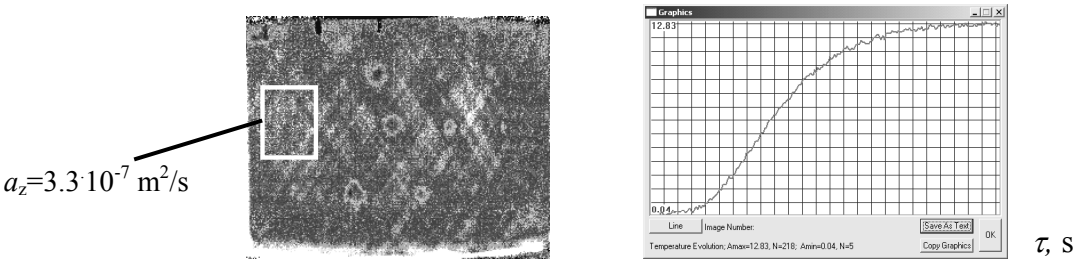
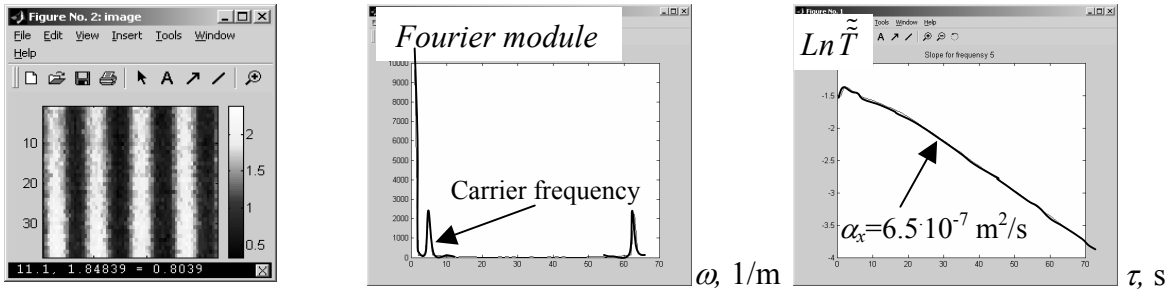


Fig. 2. Determining thermal diffusivity of a conical graphite/epoxy composite sample by applying IR TNDT (left-IR image, square area for averaging a_z, right – Parker's temperature response used for calculating a_z)

A rather new area of academic and applied interest is the determination of diffusivity lateral components a_x, a_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 from Innovation, Ltd. that allows to model a composite consisting of up to 30 layers (plies) arbitrarily tilted in regard each to other.

The main problem when applying the Fourier transforms technique is choosing an optimum spatial frequency for calculating a_x, a_y. Our most trust-worthy results have been obtained by using a slit-mask technique proposed by Krapez et al. [3]. Unlike the arbitrary heating method, this technique allows the easy choice of a proper carrier spatial frequency ω. The steps of the slit-mask procedure are illustrated by Fig. 3. An IR image produced by slit-mask results in a well-recognizable pattern (Fig. 3a) which is characterized by a particular spatial frequency (carrier frequency). This frequency is well seen in the Fourier spectrum (Fig. 3b). The final step of the algorithm involves determining the slope of the logarithmic 'Fourier temperature' vs. time τ that is numerically equal to the material thermal diffusivity (Fig. 3c) along the coordinate perpendicular to the slit direction.



a) **b)** **c)**

Fig. 3. 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 a_x

4. Defect detection

Since thermal properties of a material are determined, defect detection limits can be evaluated by comparing *significant* detection parameters, such as temperature signals $\Delta T(\tau)$ and contrasts $C(\tau) = \Delta T(\tau) / T(\tau)$, with experimental estimates of noise adherent to particular materials. In application to graphite/epoxy composites, IR TNDT detection limits can be evaluated by applying the following rules: 1) surface temperature must not typically exceed 100°C, 2) defect signals 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. 4.

The above-described approach requires determining experimental noise values $\Delta T_n(\tau)$ and $C_n(\tau)$. The corresponding evolutions are shown in Fig. 5 for a graphite/epoxy. It is seen that noise temperature signals ΔT_n in a small rectangular area, which is assumed to be sound, decay from 0.35 to 0.2°C starting from the end of the heat pulse, while the temperature contrast C_n grows up from 2 to 3% due to low excess temperature at the end of the thermal process. These estimates have been obtained in the absence of reflected radiation and they match well earlier-published data.

a) **b)**

Fig. 4. Two-sided IR TNDT of a 15 mm-thick graphite/epoxy composite (10 s heating):

a – optimum source image,
b – map of defects compiled by phasegram (correct detection 100%, false alarm 10%)

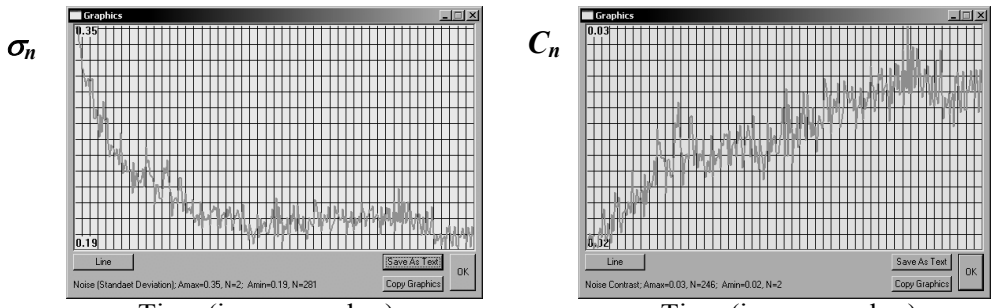


Fig. 5. Analyzing 'one-sided' surface noise in a graphite/epoxy composite

The difference between detection parameters is that signals ΔT are proportional to heating power, while contrasts C characterize particular defects, therefore, the latter parameter should be used for evaluating detection limits. By other words, only such defects can be reliably detected which produce temperature contrasts above a noise level. The example of this approach is presented in Table 1 which has been derived by comparing calculated maximum C_m values (ThermoCalc-6L) and the noise threshold which assumed to be 1% as the best practical estimate of an experimental noise. The detection limits for three types of thick composites are given as the combinations of three defect parameters: diameter D, thickness d and depth l. Square-pulse and flash heating are presented for both one-sided (***F***-surface) and two-sided (***R***-surface) procedures. For example, it is immediately seen that flash heating is useless when inspecting thick ceramics.

5. Defect characterization

Defect characterization represents the most difficult task. First of all, mathematically, it is a fascinating area of research intended for solving ill-posed problems of heat conduction. Unfortunately, many available theoretical algorithms are time-consuming and can be hardly used in practice. More simple solutions involve analytical formulas which arrive from the classical heat conduction theory 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 the advanced processing of IR image sequences. A unique defect characterization option available in ThermoFit Pro allows the evaluation of defect lateral size, depth and thickness.

There are three main defect parameters to be evaluated:

- defect (lateral) planar dimensions (in the projection onto surface inspected),
- defect depth l,
- defect thickness d, or thermal resistance $R_d = d / \lambda$.

It has been shown elsewhere that, if a signal-to-noise ratio is relatively high, subsurface defects produce well-visible surface 'footprints' of whose dimensions represent good estimates of true defect size and shape. Therefore, the simplest technique to determine defect lateral dimensions is just to measure their surface footprints by using some kind of a reference. Among more sophisticated techniques for determining defect lateral size, the following ones can be mentioned: 1) measuring distance between the extremums of the first derivative (the main problem here is enhancement of high-frequency noise), 2) measuring distance at 50% of ΔT signal amplitude (the so called FWHM-Full Width Half Maximum technique).

The ThermoFit Pro software includes the inversion algorithm which involves also maximum ($D_{\max}$) and minimum ($D_{\min}$) dimensions of defects which are to be determined by the operator. The

Table 1

Theoretical limits in detecting air-filled defects in graphite/epoxy, ceramic and glass fiber reinforced plastic materials (noise temperature contrast is 1%)

Depth detection limits by defect depth l					
Graphite/epoxy		**Ceramics**		**GFRP**	
F-surface	***R***-surface	***F***-surface	***R***-surface	***F***-surface	***R***-surface
***L* = 4.9 mm**		***L* = 10 mm**		***L* = 10 mm**	
Square- pulse heating		***Square-pulse heating***		***Square-pulse heating***	
4 mm (*D* =10 mm, *d*=0.1 mm) *	At any depth (*D* =10 mm, *d*=0.1 mm)	< 5 mm (*D* =10 mm, *d*=0.5 mm)	At any depth (*D* =10 mm, *d*=0.5 mm)	< 5 mm (*D* =10 mm, *d*=0.5 mm)	At any depth (*D* =10 mm, *d*=0.5 mm)
3 mm (*D* =5 mm, *d*=0.1 mm)	At any depth (*D* =5 mm, *d*=0.1 mm)	< 5 mm (*D* =5 mm, *d*=0.5 mm)	At any depth (*D* =5 mm, *d*=0.5 mm)	< 5 mm (*D* =5 mm, *d*=0.5 mm)	At any depth (*D* =5 mm, *d*=0.5 mm)
3 mm (*D* =10 mm, *d*=0.05 mm)	At any depth (*D* =10 mm, *d*=0.05 mm)	< 5 mm (*D* =10 mm, *d*=0.25 mm)	At any depth (*D* =10 mm, *d*=0.25 mm)	< 5 mm (*D* =10 mm, *d*=0.25 mm)	At any depth (*D* =10 mm, *d*=0.25 mm)
Flash heating		***Flash heating***		***Flash heating***	
4 mm (*D* =10 mm, *d*=0.1 mm)	At any depth (*D* =10 mm, *d*=0.1 mm)	Defects not detected		< 5 mm (*D* =10 mm, *d*=0.5 mm)	At any depth (*D* =10 mm, *d*=0.5 mm)
3 mm (*D* =5 mm, *d*=0.1 mm)	At any depth (*D* =5 mm, *d*=0.1 mm)			< 5 mm (*D* =5 mm, *d*=0.5 mm)	At any depth (*D* =5 mm, *d*=0.5 mm)
3 mm (*D* =10 mm, *d*=0.05 mm)	At any depth (*D* =10 mm, *d*=0.05 mm)			< 5 mm (*D* =10 mm, *d*=0.25 mm)	At any depth (*D* =10 mm, *d*=0.25 mm)

* L -material thickness, D - defect diameter, d – defect thickness

inversion formulas have been obtained for some types of composite materials:

$$l = \varepsilon_1 L^{\alpha_1} C_m^{\beta_1} [a(\tau_m - \tau_h)]^{\gamma_1} (D_{\min}/L)^{\sigma_1} (D_{\max}/L)^{\nu_1} Fo_h^{\chi_1},$$
$$d = \varepsilon_2 L^{\alpha_2} C_m^{\beta_2} [a(\tau_m - \tau_h)]^{\gamma_2} (D_{\min}/L)^{\sigma_2} (D_{\max}/L)^{\nu_2} Fo_h^{\chi_2}, \quad (1)$$

where $\varepsilon, \alpha, \beta, \gamma, \sigma, \nu, \chi$ are the constants (not reported here for the non-disclosure reason), τ_m-best observation time, τ_h-heat pulse duration, L-sample thickness, and $Fo_h = \alpha_z \tau_h / L^2$-Fourier number. The work of this algorithm is illustrated by Fig. 6 where the ThermoFit Pro 3D defect characterization window is shown. An image to be analyzed should exhibit some areas of interest which are suspected to be defective. In the program, these areas are highlighted by using the Sobel filter and imposed on the source image. Then, the operator determines defect dimensions $D_{\max}$ and $D_{\min}$, as shown in Fig. 6. The crucial step in using the algorithm (1) is the calculation of a contrast of which time evolution is to be 'classical', i.e. to exhibit a distinct 'positive' maximum $C_{run}^{\max}$, such as shown in Fig. 6 on the right. Typically, a defect central point and a neighbor non-defect point should be chosen for determining $C_{run}^{\max}$.

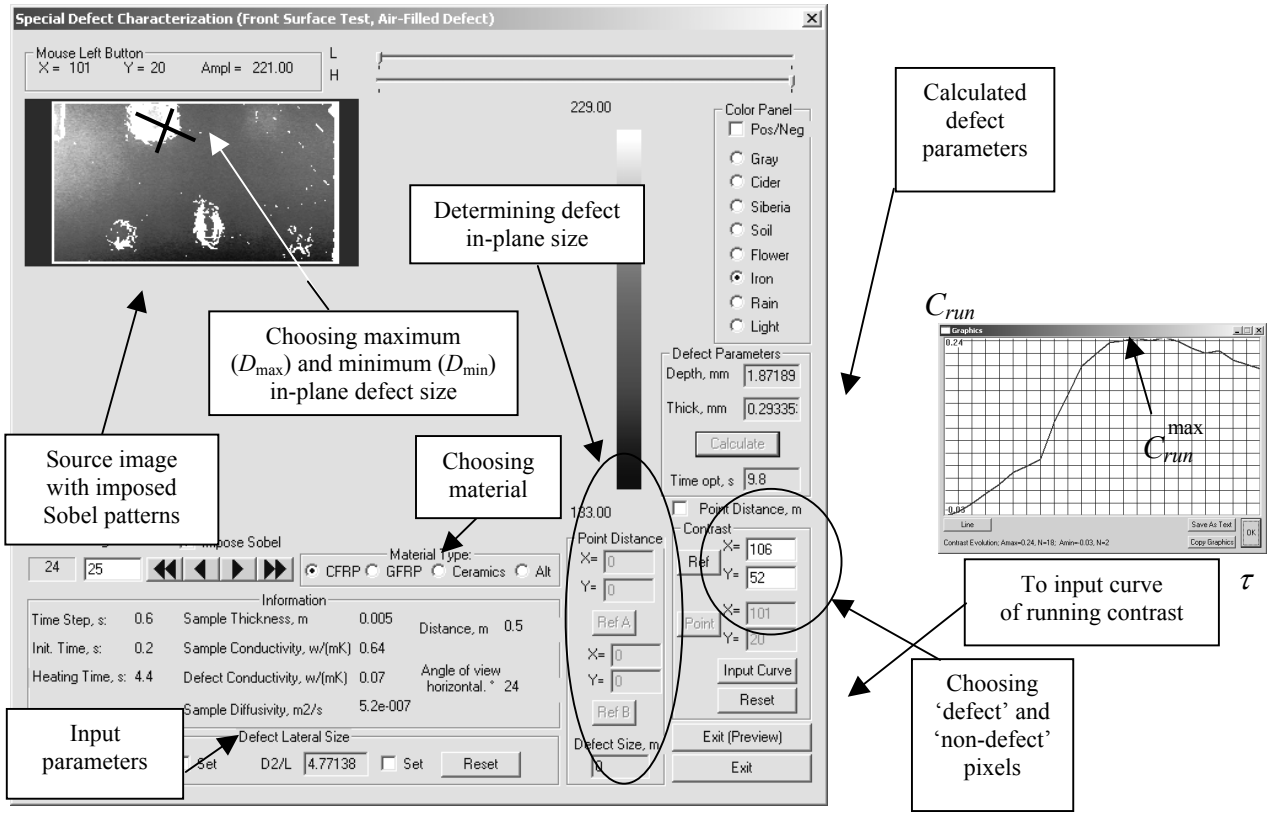


Fig. 6. 3D Defect Characterization window in the ThermoFit Pro

6. Conclusion

- Composite materials which are widely used in the aero space industry remain the most successful objects for the application of thermal/infrared NDT. On the academic level, NDT of these materials represents the scientific field where algorithms for solving inverse heat conduction problems are being explored. From the practical point of view, it can be stated that both the commercially-available IR imagers and the modeling/processing software are matured enough to allow designing and practical implementing of TNDT devices intended for non-invasive inspection of composite materials.
- The advantage of IR thermographic procedures is that they can be used for both the determination of thermal properties and the detection and characterization of hidden defects in a single experimental test. Development of the corresponding algorithms is related to modeling, i.e. solving direct heat conduction problems (ThermoCalc-2D, ThermoCalc-6L and ThermoCalc-30L software).
- Characterization of defects by their surface 'footprints' is one of the most fascinating research areas in TNDT. Defect lateral dimensions can be evaluated relatively easily by direct measurement, while determining defect depth and thickness requires solving inverse heat conduction problems. A rather simple approach to defect characterization is implemented in the ThermoFit Pro software.

References

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