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Hardware and Software for Thermal Nondestructive Testing of Metallic and Composite Materials

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Abstract. Modeling and processing software, as well as experimental units, developed at Tomsk Polytechnic University for the last decade in the field of thermal/infrared nondestructive testing, are shortly described in this paper along with some illustrations of using this technique in the detection of impact damage in composites and corrosion in metals.

1. Introduction

A strong demand for high quality of technical installations and responsible parts in high-tech industries, such as military, aero space, automotive, ship building and power production, continues to stimulate development of novel and combined techniques of nondestructive testing (NDT). For the last decades, the so-called “big five” NDT methods have been: X-ray, ultrasonic, eddy current, magnetic particle and liquid penetrants [1]. Presently, thermal nondestructive testing (TNDT) is often included in this list as an indispensable method due to the following [2, 3]: 1) TNDT can be applied to all types of solids even if particular materials pose a certain challenge for efficient inspection, 2) TNDT is very fast, thus being considered as a screening technique operating in combination with others, 3) TNDT is illustrative, and human being’s skills in interpreting ‘images’ can be useful in treatment of infrared (IR) images, and 4) TNDT is safe and often portable that is important when conducting NDT in public places.

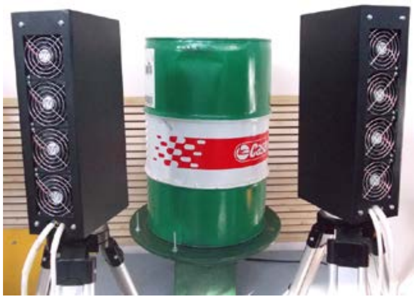
Tomsk Polytechnic University has long traditions in TNDT. In the Soviet period, the research emphasis was done on development of specialized NDT hardware based on Russian-made components, because foreign IR imagers used to be practically unavailable in the former USSR in that period of time. Since the 1990s, the research focus was shifted onto software, both for modeling and data processing. Two major software packages have been developed and continuously modernized for the last years: ThermoCalc-6L and its modifications (simulation of TNDT problems) and ThermoFit Pro (processing experimental and synthetic IR image sequences).

Presently, certain efforts are being inputted in the development of a portable unit for performing active thermal NDT in both laboratory and outdoor conditions.

First of all, the research target is inspection of composite materials, mainly used in aviation, such as carbon and glass fiber reinforced plastics (CFRP and GFRP) and honeycomb structures. Another research area is the detection of hidden corrosion in above-ground steel tanks, piping, tanks, etc. In both areas, the above-mentioned advantages of TNDT are fully realized.

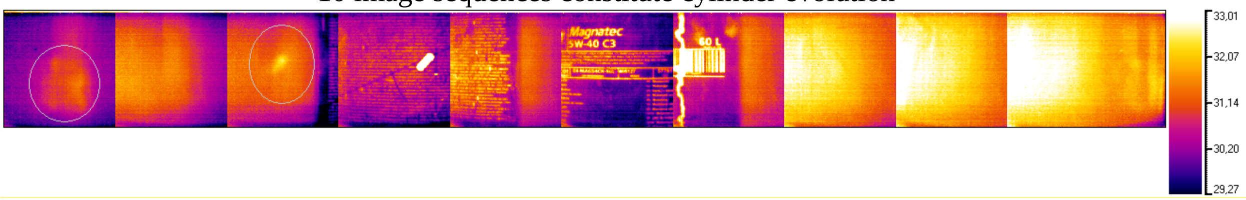
2. TNDT setups

The concept is to develop both experimental laboratory systems and portable units for in-field inspection. A flexible laboratory system for active TNDT is shown in figure 1a in its implementation to corrosion detection in steel containers intended for keeping low-active radioactive wastes. A cylindrical test object is rotated being stopped for about 20 seconds needed for inspection in each position. An IR imager captures from 20 to 100 IR thermograms which are processed, and results are exhibited as raw or binary images. Images taken at each check position are composed to present circular evolution of temperature (figure 1b). Several IR imagers can be used in this system (FLIR P-65, Nec Avio-9100, FLIR-A325 SC and FLIR SC 7700M IR cameras are currently used at Tomsk Polytechnic University). There are a couple of heat sources which are used in the system, for instance: 1) Xenon flash lamps, and 2) halogen lamps (shown in figure 1a).



a)

10 image sequences constitute cylinder evolution



Binary map of defects produced by means of neural network

b)

Figure 1. Laboratory setup for active TNDT including NEC Avio IR camera and 2 halogen lamp heaters (a) and example of test results (b).

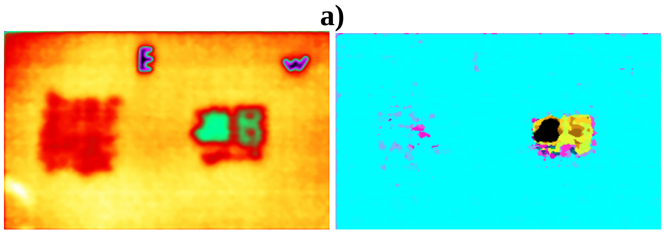
A portable IR thermographic unit implements the same principle of active TNDT but allows out-door operation by one or two thermographers. The current unit is presented in figure 2a. Four halogen lamps 500 W each illuminate an object to be tested, such an airplane panel, for a controllable time (typically, 3-15 s). Since the heat source is turned off, its residual thermal radiation is cut off by means of a 4-lamella mechanical shutter thus preventing reflected radiation that is a notorious source of noise in one-sided TNDT.

The illustrations of using the portable unit in NDT are shown in figure 2b, c. When checking airplane panels made of honeycombs, there is an inspection problem of distinguishing between water and epoxy glue hidden in honeycomb cells. Water represents a serious exploitation problem because its presence leads to honeycombs damage [4]. However, water surface thermal ‘footprints’ can be easily confused with those of epoxy glue due to close amplitudes of differential temperature signals

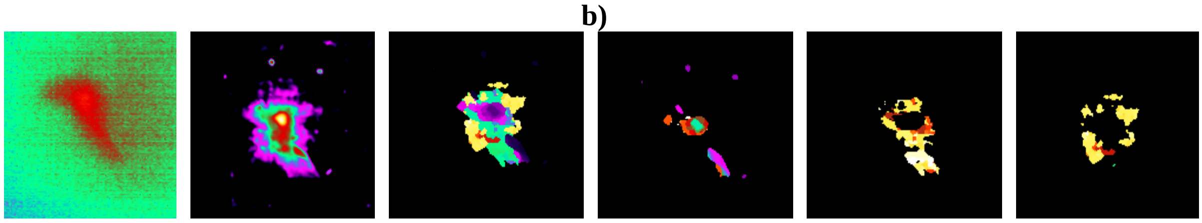
ΔT (figure 2b, left). However, specialized data treatment based on the analysis of the $T(\tau)\cdot\tau^n$ synthetic temperature function as a novel processing algorithm proposed in [5] allows fairly good discrimination between two defective sites (figure 2b, right).

Another example of using TNDT in the inspection of impact damage in a 4 mm-thick CFRP sample (low-velocity 59 J impact) is presented in figure 2c. The raw temperature image bears no detailed information about structure of the induced defect. Better results have been obtained by applying the algorithms of dynamic thermal tomography proposed at Tomsk Polytechnic University in the 1980s, see more details the recent paper [6]). The tomograms in figure 2c exhibit sample structure within three different layers and clearly show that cracks (delaminations) induced by the impact are minor on the impacted surface but become larger with material depth, This is in accordance with the known fact that impact damage can be invisible on the airplane outer surface but cause significant damage deeper in the composite, often closely to the panel rear surface.

a)



b)



Best raw image	Maxigram	Timegram	Tomogram (0.43-0.89 mm)	Tomogram (1.03-1.63 mm)	Tomogram (1.92-2.27mm)

c)

Figure 2. Portable IR thermographic NDT unit and examples of test results: a – unit photo; b – distinguishing between hidden water and epoxy glue;in honeycomb panel (left – best raw image, right – result of processing by using the analysis of $T\cdot\tau^{0.43}$ synthetic function [5]); c – thermal tomography of impact damage in 4 mm-thick CFRP sample (one-sided inspection, 59 J impact energy).

Some technical characteristics of the portable unit from figure 2a are given in table 1.

Table 1. Technical characteristics of portable IR thermographic NDT unit (figure 2a).

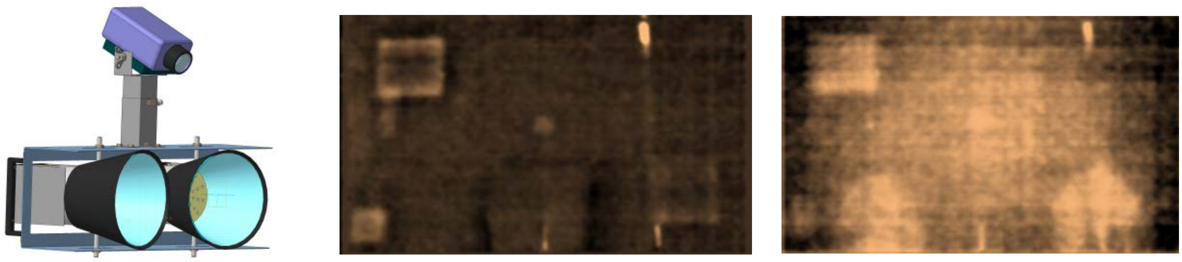
Parameter	Value
Test objects and their thickness	Steel, titanium, aluminum (up to 6 mm*) CFRP and other composites (up to 4 mm*)
Test area	0.04 m^2
Test productivity	4.7 $m^2 \cdot hr^{-1}$
Minimum detectable materials loss in steel **	10 %
Minimum lateral size of detectable defects in composites **	10 mm
Temperature sensitivity	0.02-0.06 ^oC ***
Power supply	220 V AC
Mass	5–10 kg

* Depending on a used heat source

** Depending on sample thickness and some test parameters

***Depending on a used IR imager

Another concept of a portable IR thermographic NDT unit is shown in figure 3a. It differs from that in figure 2a by the use of two LED heat sources, 500 W each. Such heaters only recently started to be used in TNDT. Their advantage in comparison with lamps is the monochromatic operation mode involving radiation in the visual band from 0.3 to 0.7 μm. Since IR imagers normally operate at wavelengths from 3 to 5 or from 7–13 μm, LED heaters produce no reflected radiation sensed by IR imagers. Unfortunately, because of high reflectivity of many materials at these wavelengths, the LED radiation may be inefficient to warm a test sample up to a required temperature. The corresponding illustration is given in figure 3b in the detection of hidden corrosion 25 % material loss in a 1 mm-thick steel sample) by using both halogen lamps and LED heaters. This example shows that LEDs provide worse detection results although their power is much less than in the case of 30 kW halogen lamps.



a) b)

Figure 3. Concept of a portable IR thermographic unit using LED heat source (a) and corrosion detection in 1 mm-thick steel sample by applying 30 kW halogen lamps (left) and 2×500 W LEDs (right) heat sources; the sample contained 5 sites of rear-surface 25 % material loss of different size.

3. Determining TNDT detection limits

It is very typical for end-users to ask about detection limits of NDT methods and particular equipment. To answer this question is particularly difficult in TNDT because test results depend on many factors, such as defect size by all coordinates, defect depth, type of material and surface conditions, type of a used heat source, wavelength band, IR imager temperature resolution, etc.

The corresponding approach allowing the evaluation of minimum detected defects has been proposed by combining results of modeling and experimental estimates of the noise adhering to each particular test case.

Modeling is done by using a software package developed at Tomsk Polytechnic University and allowing calculation of surface temperature signals in 1D, 2D and 3D cases. The Layer-3 Analytic, ThermoCalc-2D and ThermoCalc-36L programs with their many modifications are simple and robust enabling calculation of temperature distributions over hidden defects. The main calculated parameters are differential temperature signals ΔT_m and temperature contrasts C_m, as well as times of their appearance τ_m.

A detailed description of modeling is beyond the scope of this paper, see the handbook [2]. Let us consider the detection of delaminations in CFRP as an example. The temperature signals that can be achieved in this test case depend on defect depth and size and duration of heating, as demonstrated by figure 4, where the curve family has been calculated by using the ThermoCalc-36L software for solving the corresponding 3D heat conduction model (see details in [3]). The contrast $C=\Delta T/T$ is a dimensionless parameter which shows a relative temperature signal in regard to sample excess temperature T. Each material, while being heated, is characterized by the temperature noise contrast conditioned by uneven heating and surface clutter. It is important that such noise increases proportionally with excess temperature, therefore, it can be expressed in percent to characterize each particular material. For example, it has been experimentally found that CFRP composite has noise contrast from 1-2 %, hence, its level is often assumed to be 5 % (at the level of 2-3 standard deviations). If to draw a horizontal line in figure 4 corresponding to 5 %, its crossings with family curves will specify minimum detectable defects. It follows from figure 4 that, in one-sided TNDT of a 5 mm-thick CFRP samples, delaminations of various lateral size and thickness can be detected to the depths of 3.3-4 mm that matches well earlier published experimental results [2].

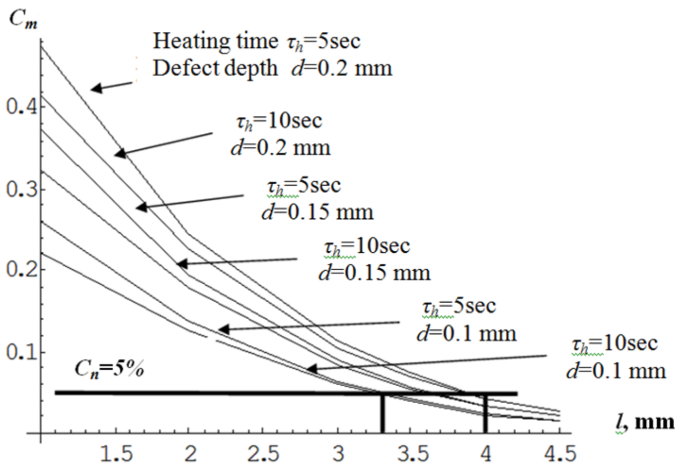


Figure 4. Determining defect detection limit by depth in TNDT of 5 mm-thick CFRP.

The same approach applied to the detection of corrosion in steel is shown in figure 5. The thickness of steel samples heated with a thermal pulse was 1, 5 and 10 mm and the size of a corroded area was 10×10 m. The noise level was assumed 10 % that corresponds to many painted metallic surface. It is seen that, in this case, the detection limit is 10-40% by material loss depending on sample thickness.

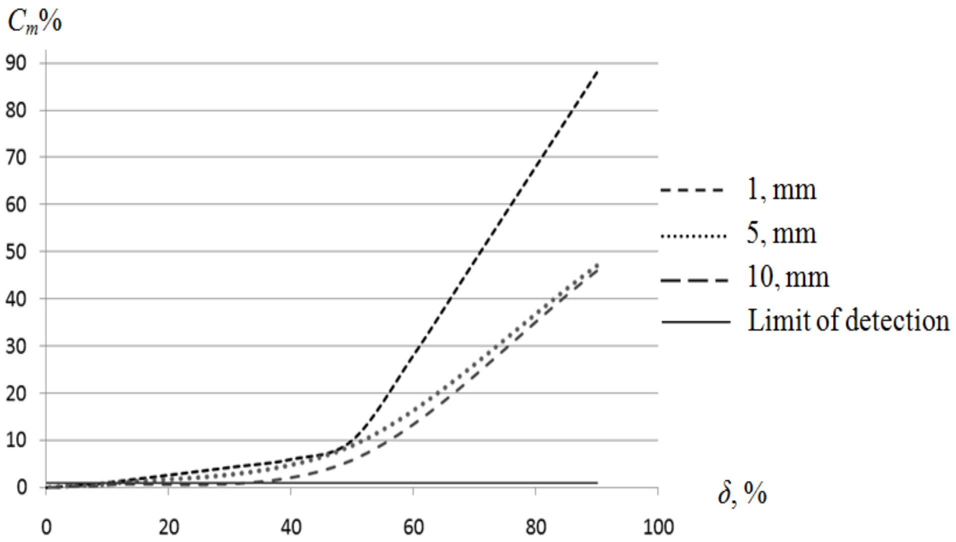


Figure 5. Determining corrosion detection limit by material loss in steel.

4. Conclusion

A universal character of thermal/infrared NDT allows developing universal inspection units which may be used for testing a wide range of materials and objects. This feature, along with illustrativeness and high productivity of the thermal methodб makes it attractive as a screening inspection technique which can be used solely or in combination with other NDT methods. Composites constitute the most successful application area for thermal NDT, particularly, in aviation where large areas subject to NDT and safety requirements make difficult using other NDT methods. Another perspective application area is the detection of corrosion in metallic shells. The thermal/infrared NDT research being conducted at Tomsk Polytechnic University involves the development of both software and hardware, as well as inspection guidelines and approaches for determining NDT limits.

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