http://dx.doi.org/10.21611/qirt.1992.028

Thermal non destructive testing: short history and state-of-art

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Abstract

History of thermal non destructive testing could be traced up to the first patents concerning the distant detection of warm objects. In more narrow sense this method includes the heat stimulation of a specimen and measurement of its temperature-in-time response. Theoretically, thermal testing involves the solving of direct and inverse heat transfer problems. Variations of thermal properties and presence of internal defects disturb dynamically the thermal pattern of a specimen. Experimentally, the infrared equipment is mostly used. Infrared imagers are able to produce the space-domain and time-domain images which could be calibrated in diffusivity or effusivity values, defect depth or thickness. Image processing techniques could suppress the noise caused by structural non-uniformity, non-even heating and background radiation. Thermal testing application fields concern the composites and layered materials used in aerospace, building and oil & gas industry.

Nomenclature

α	diffusivity [$m^2.s^{-1}$]
θ	dimensionless temperature
ρ	density [$kg.m^{-3}$]
τ	time [s]
τ_m	timewhen ΔT or A reach the maximum [s]
τ_r	relaxation time [s]
A	temperature contrast upon the defect
C	heat capacity [$J.kg^{-1}.K^{-1}$]
D	defect size [mm]
ΔT	excess temperature signal upon defect [K or ^oC]
e	effusivity [$W.s^{1/2}.m^{-2}.K^{-1}$]
K	conductivity [$W.m^{-1}.K^{-1}$]
l	defect depth [mm]
q	volumic power density [$W.m^{-3}$]
R	thermal resistance of defect [$m^2.K.W^{-1}$]
T	absolute temperature [K]
t_h	excess temperature above ambient [K or ^oC]
T_m	maximum excess temperature of a specimen [K or ^oC]
W	absorbed energy density [$J.m^{-2}$]
x,y,z	coordinates

1. Introduction

The term thermal non destructive testing (TNDT) internationally refers to the detection of subsurface defects in materials using the transient (active) or, more rarely, steady-state (passive) one- and two-side procedure. In Russia this term often includes the predictive maintenance, building and sometimes even medical applications underlying the non-invasive character of physical operations with objects to be tested. In this paper we shall deal mostly with composites and layered materials assuming the TNDT procedure as analysis of locally distributed or averaged thermal properties. The internal defect(s) could be considered as sharp or smooth variations of thermal properties. Particular applications fields are intentionally omitted in order not to be dispersed over this vast area but to be more concentrated on the new TNDT concepts.

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2. Short TNDT history

Because of its physical principle the TNDT could hardly be distinguished from similar problems of infrared (IR) reconnaissance, building, energetics, medicine and other areas where the thermal effects occur. The signs of TNDT procedure could be traced up to beginning of our century (see excellent review of IR research by R.D.HUDSON [1]). R.D.PARKER patented the IR iceberg detector in 1914 [2] although the attempts to sense distantly the animals and human beings have been even done in the XIX century by using the thermopile detectors. G.A.BARKER proposed the IR system to detect forest fires in 1934 [3]. One of the first industrial applications of IR technique concerned the analysis of heating uniformity in hot steel strips (J.T.NICHOLS, 1935 [4]). Modern effusivity analysis follows from the earlier work of P.VERNOTTE published in 1937 [5]. From the 60-s IR technique was used for NDT of electronic components. Probably the first transient NDT test which was described by W.S.BELLER in 1965 [6] involved the inspection of Polaris missiles motor casings placed in the warm premise. At the 1965 Spring National Convention of the Society for NDT, USA, up to 40 % of papers were devoted to the IR method. These historic reminiscences just mean that we have to be very careful when confirming our priority in the *new* TNDT techniques. In fact most of basic TNDT ideas which are still valuable now have been reported in 60-s (see works of D.R.GREEN [7], F.E.ALZOFON [8] which are full of useful remarks for modern researchers). By that time the previously classified information about possibilities of IR military technique started to penetrate the civil engineering areas. This fact was clearly shown by TNDT bibliography compiled by S.MERHIB and R.TAYLOR in 1972 [9].

To the end of 70-s the *take and try* approach has been apparently exhausted and did not provide the succesful competition of TNDT with other methods. New level of understanding was achieved by use of heat transfer basics summarized by H.S.CARSLAW and T.S.JAEGER [10] in the West and A.V.LYKOV [11] in Russia. Description of defects as the areas with changed thermal properties has been introduced into related theoretical solutions providing the better understanding of TNDT mechanism. Such approach was described by D.BALAGEAS [12],V.VAVILOV and R.TAYLOR [13], P.V.MCLAUGHLIN and H.G.MIRCHANDANI [14]. As a result, it became possible to combine the efforts of IR specialists and those working in heat transfer theory. New fields of TNDT interests involved effusivity and diffusivity measurements [15-17].

Nevertheless for some period of time the TNDT problems did not represent the special academic interest for heat transfer theory. This situation changed when characterization of defects required solution of inverse problems. In fact many aspects of human activity are connected with inverse procedures and any NDT method gives the application field for non-correct problems. Computerized thermography systems including artificial intelligency elements are developed now to extract the information about discontinuities and variations of thermal properties hidden under the surface [18-20].

Modern TNDT involves the wide use of image processing technique borrowed from the original areas of its applications (aerospace reconnaissance, medicine). New procedures are mostly based on the processing of temperature-time data.

Thermal NDT survived some up-and-down jumps of interest since 60-s. Now it is highly integrated area incorporating the achievements in heat transfer, IR techniques, image processing, etc. In fact the ideology of TNDT of composites and layered materials has been formed during the five last years [18]. The constantly growing interest to TNDT conditioned by high productivity, distant and rather universal character of measurements and non-harmful operation could be followed to many international forums (like the annual *Thermosense* and Quantitative NDT meetings in the USA, European *Eurotherm* seminars, World NDT Conferences, Conferences on Thermal Engineering in Hungary, some meetings in Russia, USA, France, etc.). TNDT bibliography written by D.D.BURLEIGH has covered the period up to 1986 [21]. Some books including *Handbook of TNDT* and review of Russian aerospace research have been published by V.VAVILOV [22-24]. In 1992 two exhaustive books are to be issued by efforts of X.MALDAGUE [25,26]. Just for illustration there is the chart of works published on TNDT of layered materials during 1976-1991 in *figure 1* (with total number of works equal to 374).

New possibilities could be opened in future after combination of TNDT and other NDT methods, especially ultrasonics. Another field of activity covers certification and standardization problems. For example, the use of infrared thermography is industrially recognized in predictive maitenance although even in this field the American Society for NDE still does not view TNDT as reliable tool.

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Infrared NDT technique for materials analysis is not so developed like IR detection of overheated joints and heat losses. Its use for real cost savings purposes is only done by a few organizations which are able to make rather big initial investments (General Dynamics and NASA in USA, ONERA and Dassault Aviation in France). Nevertheless the TNDT methods have favourable future especially in the aerospace industry where possibility to check the constantly emerging new materials falls behind the possibility to design and manufacture them.

3. Basic procedures

New TNDT procedures described below are under intensive development now. Here we refer to the basic physical procedures.

The TNDT stages include thermal excitation resulting in creation of the useful signals from the internal defects on the specimen's surface, temperature measurement with real time data processing, post-processing and decision making with participance of human brain or artificial intelligence.

Heuristic or automated decision making could be viewed as functional procedure dealing with pre- or/and post-processed 3D temperature-time information. In the simple but very practical case it could mean the pattern recognition in 1D space of particular TNDT parameter (i.e. the intensity of IR radiation or specific heat transfer time could serve as this parameter).

In its turn the process of temperature measurement represents the functional transformation of IR radiation intensity into electrical signal involving the absorptivity-reflectivity-emissivity effects, atmosphere transparency, detector's properties, etc. Thermal excitation functional could be introduced at this stage too although for some practical reasons it is often analyzed as the independent operation.

Physical processes which occur in the tested object are described with heat transfer differential equation and could be regarded too as the next functional. It includes external and internal thermal parameters producing the 3D set of temperature data $T(x,y,\tau)$ (for semi-transparent materials it could be even 4D set representing more difficult case). Frequently the $T(x,y)$ distribution is called as *thermogram* and $T(\tau)$ function is specified as *chronological thermogram.*

It is clear from considerations above that tested object and processes inside it represent the crucial point in any TNDT procedure. Each solid is specified with 3D distribution of thermal parameters $K(x,y,z)$; $\alpha(x,y,z)$ If the corresponded functions are continuous we deal with materials analysis (i.e. with effusivity measurement). Any discontinuity of these functions could be regarded as internal defects (voids, combs, etc). Formally speaking, the temperature response $\Delta T(x,y,\tau)$ on the surface is the result of functional acting on the particular internal point x,y with specific values of K, α. Because of strong heat dissipation and time delay the optimum point of signal measurement has to coincide in ideal case with the point which caused this signal. It was shown that Dirac heat source scanning the volume with later measurement of temperature response of each point produces the maximum useful signal [22]. In a case of opaque solid the optimum recorded point has to be chosen just upon the defect. So the basic signal is temperature difference $\Delta T(x,y,\tau)$ between defect and non-defect point. Temperature contrast which unlike $\Delta T(x,y,\tau)$ value does not depend on the heating power density is often introduced in the following way:

$$A(x,y,\tau)=\Delta T(x,y,\tau)/T_{nd}(x,y,\tau) \qquad \text{or} \qquad C=1+A$$

where *nd* relates to non-defect area.

Phylosophy above is only intended to prove the decisive role of specimen's parameters in determining the TNDT limits. Any real specimen is characterized by noise volumic distribution of K, α values with defect being regarded just like a component of this noise. Moreover there could be noise distribution of surface optical parameters in the IR procedures, i.e. emissivity and absorbtivity noise. *It is obvious that statistical values of informative parameters measured in non-defect areas limit the TNDT sensitivity.*

Basic TNDT procedures are shown in *figure 2*: standard point heating with delayed point temperature measurement (*figure 2a*) (non-movable beam allows to investigate the isotherm pattern); the same with temperature measurement by deflection of probing laser beam - *mirage*

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technique (*figure 2b*); photoacoustic technique by photodeformation (*figure 2c*); line heating and line scanning technique (*figure 2d*); standard thermographic procedure (*figure 2e*); two-side *flash* procedure originally proposed for diffusivity measurement (*figure 2f*); mechanical loading of a specimen (*figure 2g*); use of internally injected hot or cool agent (*figure 2h*) (i.e. detection of blocked passages in turbine blades); *side* heating to detect the perpendicular-to-surface cracks, i.e. in turbine blades (*figure 2i*); use of electrical heating of metals (*figure 2j*); inductive heating of metal-non-metal specimens (*figure 2k*); detection of moistened areas by decreased temperature due to evaporation process (*figure 2l*). Notice that many procedures could be fulfilled in one- (reflection mode) or two-side (transmission mode) variants with different $W(x,y,\tau)$ functions. Another TNDT terminology (*videothermography, flying spot, synchronous vector lock-in* and *box-car* techniques *et al.*) is described in [27]. Some new procedures are discussed below.

4. Governing equations

The governing heat transfer equation for anisotropic body is:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right)+q=\rho C\frac{\partial T}{\partial \tau}+\rho C\tau_r\frac{\partial^2 T}{\partial \tau^2}.$$

Modern TNDT tests still do not reach the time resolution specified for extremely quick (explosive) thermal processes described with relaxation time τ_r (finite speed of heat). In many cases volumic power density is absent so the commonly used heat transfer equation is:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right)=\rho C\frac{\partial T}{\partial \tau}$$

or for isotropic material:

$$\alpha\nabla^2 T=\partial T/\partial\tau$$

We do not discuss here the boundary conditions on the external surfaces which are well known. As for border between sound material and defect, there are simple equations which fix the continuity of heat flux and temperature:

$$K_s(\partial T_s/\partial\bar{n})=K_d(\partial T_d/\partial\bar{n})$$

$$T_s=T_d$$

where *s* and *d* specify specimen and defect.

Often the K,α values for defect are replaced with K value specifying the thermally resistive defect:

$$T_1-T_2=RK_1(\partial T_1/\partial\bar{n})$$

5. Thermal NDT as inversion heat transfer problem

It is clear that temperature measurement is not the goal pursued by operator. Final decision about quality depends on the information about parameters of defect found as a test result. In a simple case this includes the characterization of defect depth and size, i.e. parameters influencing the surface temperature distribution. Defect sizing problem would be solved easily if surface temperature would depend on the defect parameters in a simple algebraic way. Unfortunately, the equations involved are highly complicated and require special solution algorithms. In the direct heat transfer problem the small variations of input data (defect parameters) usually cause the small variations of output data (temperature). *In the inverse procedure even low-level temperature noise causes essential variations of obtained defect parameters.* It simply means that different combinations of defect parameters (depth, size and conductivity) could produce the close temperature signals.

Algorithms proposed for solution of inverse problems include:

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- compiling the calibration curves as a result of multi-fold calculations of direct problem;
- iterative calculation of direct problem approaching at the each step theoretical and experimental results;
- methods based on the *a priori* known or directly measured empirical data about some defect parameters.

More information on the inverse TNDT problems could be found in references [19,27-29]. But so far no one of these methods was absolutely successful being either too time-consuming or limited with special cases.

6. Direct solutions

Direct TNDT solutions are still highly necessary allowing to:

- understand better the TNDT mechanism and investigate the topology of temperature fields;
- outboard the second-hand parameters and choose the best informative criteria;
- determine the TNDT sensitivity in the presence of structural and apparatus noise.

6.1. Analytical solutions for a plate: thermal properties measurements

A lot of published works deal with thermal properties measurements based on the expressions well known in heat transfer theory. New step in such considerations is represented by attempts to extract from these expressions the information about dispersed or localized defects.

Dirac flash point heating of thermally thick specimen is given by :

$$\theta = t_h / T_m = Fo_x^{-3/2} \exp(-1/4\,Fo_x)$$

where $Fo_x = a\,\tau / x^2$ is Fourier number for point placed at distance x from heated point. Diffusivity of material could be found by $\alpha = z^2 / 6\,\tau_m$ where τ_m is time when θ reaches maximum. TNDT application of this model was discussed in [27].

The solution for instantaneous plane source located on the adiabatic plane $z = 0$ of semi-infinite body is the following:

$$t_h(z, \tau) = \frac{W}{e\sqrt{\pi\tau}} \exp(-z^2 / 4\alpha\tau)$$

Surface temperature is given by:

$$t_h(z = 0, \tau) = \frac{W}{e\sqrt{\pi\tau}}$$

Thermal propagation depth is determined as $\sqrt{\alpha\tau}$. It is assumed by many authors that inspection time when defect starts to reveal himself due to reflection of thermal wave is given by : $\tau = l^2 / \alpha$.

The last expression allows to determine the effusivity value as a function of time or specimen's depth and produce new kinds of images in thermographic NDT (see below).

For adiabatic Dirac pulse heating of a plate, the following expressions are valid:

$$t_h^H / T_m = 1 + 2\sum_1^{\infty} \exp(-n^2\pi^2 Fo)$$

$$t_h^R / T_m = 1 + 2\sum_1^{\infty} (-1)^n \exp(-n^2\pi^2 Fo)$$

where H and R specify the heated and rear surfaces. The last equations could be used to estimate the possibility of diffusivity and thickness measurement (we remind Parker's expression $\alpha = 0.139\,L^2 / \tau_{0.5}$, where $\tau_{0.5}$ is half-rise time for the temperature response curve at the R-surface (see *figure 2f*).

During the last years the term *thermal waves* is often used. This term could be slightly confusing because it could include harmonic oscillations or wave fronts generated by Dirac or square heating pulses. It is assumed that these fronts could be reflected by defects as single ultrasonic pulses.

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Here we refer to simple solution for semi-infinite body heated with periodic thermal flux:

$$t_h(z,\tau) = T_m \exp(-z/\mu)\sin\{\omega\tau - [(z/\mu)+\phi]\}$$

where $\mu = \sqrt{2\alpha/\omega}$ is thermal wave decrement (lengh of thermal diffusion); ϕ is phase of thermal wave. Value of μ ranges from micrometers to millimeters and could be considered as the depth estimate for detectable defects.

Another confusion could concern the frequency range. Photoacoustics deals with kHz and MHz range which is suitable for thin layers (up to tens of micrometers). Low frequency waves penetrate deeper but such procedure is time consuming so the priority is usually given to *time-resolved* TNDT test with single heat pulse.

Detection of crack in a plate could be simulated by heat transfer problem with a line heat flux Q (W/m^2) parallel to the x axis and located at y=0. Surface temperature is given by [30]:

$$t_h(y,\tau) = \frac{2Q(0,0)}{K}\left[\sqrt{\frac{\alpha\tau}{\pi}}\exp(-\sigma^2 y^2) - \frac{y}{2}\mathrm{erfc}(\sigma y)\right] \qquad \text{with} \qquad \sigma = \frac{1}{2\sqrt{\alpha\tau}}$$

6.2. Analytical solutions for multi-layer plate

Solutions above deal mostly with isotropic material without any finite-size discontinuity. Multi-layer models represent the good example of transition from thermal properties measurement to real defects. In fact two-layer plate with defect as an imperfect interface or three-layer plate with defect in the middle could be regarded as basic models. Theoretical solutions in these cases are rather complicated and we refer the reader to published works (short review see in [27]). Front-surface solutions in the *effusivity* treatment have been studied by D.BALAGEAS *et al.* [12], rear-surface solutions in the *diffusivity* treatment have been obtained by A.DEGIOVANNI [16] using the attractive quadripole method. For two-side inspection of three-layer plate, V.VAVILOV and A.IVANOV compiled the tables of TNDT sensitivity and studied some informative time parameters specified in the temperature response curve [17].

7. Real defects

7.1. General remarks

With real defects we specify finite-size ones which are involved into solution of 2D, 3D problems. This remark becomes crucial if we try to estimate the TNDT limits. There were some successful analytical solutions to these problems but their effective application requires anyway the use of computer because of bulky mathematics involved. So most of researchers use numeric heat transfer software which is commercially available [26], or home-made numeric programs written for particular TNDT models [13,14,27]. The 3D solution for moving heat source was studied by V.VAVILOV and R.TAYLOR in 1982 [13]. Description of 2D and 3D TNDT software has been done by P.V.MCLAUGHLIN and H.G.MIRCHANDANI in 1984 [14]. Now personal computers allow to compute effectively 2D cylindric model which is regarded by many researchers as the basic one. The mesh involved could be uniform or not, incorporating the real or thermally resistive defects. Computation time is usually about some minutes per one defect variant. V.VAVILOV compiled the TNDT sensitivity tables which are based on 2D cylindric model and contain all thermal and geometrical parameters of sound material and defect [27].

7.2. TNDT features

Up to twelve parameters influence the temperature field in the defect area. It converts any TNDT problem into essentially multi-parametric one. Some simplifications could be obtained by using the dimensionless approach known in heat transfer but in practice researchers prefer to specify all the involved parameters in order to make the important experimental hints and provide the correct comparison with earlier published data. The ideology of the first-order and second-order parameters seems to be still valid [13]. For example, heat exchange intensity, size and speed of moving heat beams do not essentially influence TNDT results. Oppositely, defect size and properties belong to

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the first-order parameters. Below we shall illustrate some qualitative features (see *figure 3*) referring the reader interested in quantitative data to a great deal of published works [13-17, 22-27].

Difference between one- and two-side procedures is quite important. Temperature signals from the defects ΔT on both surfaces gain maximums at the particular times (*figure 3a*). The same conclusion is valid for contrast A^H on the heated (H) surface but on the rear (R) surface contrast A^R is continuosly decreasing in time (*figure 3b*). Optimum measurement time in two-side procedure has to be chosen as compromise between decreasing in time contrast and absolute temperature signal having a maximum. It is worth mentioning too the so called *inversion* of defect signal sign which is rarely discussed by researchers (curves in *figure 3a,b* cross the time axis but produce low signal). For characterization of defect it is crucial that specific time parameters (i.e. τ_m) depend strongly on the defects' depth on the H-surface and not vary much on the R-surface (*figure 3c*). It means that two-side procedure is suitable for characterization of defect diffusivity (or thermal resistance) but not for measurement of defect depth l. In many practical cases the $\tau^H{}_m(l)$ dependence could be approximated with a linear function[27]. Temperature signals on the R-surface are not changing much with defect depth being limited by total thickness of a specimen but on the H-surface these signals decrease exponentially with depth (*figure 3d*). All TNDT parameters depend on the defect size D exponentially with saturation (*figure 3e*) so for non-metals the ratio of $D/l \sim$ 6-8 gives the transition from 1D to 2D or 3D problem. Finally, it is interesting to compare the distributions of temperature (*temperature domain*) and specific heat transfer times (*time domain*) shown in *figure 3f*. The τ_m profiles are steeper and produce more operator-friendly images (see below).

8. New physical procedures

Novel physical procedures could be introduced by:

- providing the new displacement of heater, specimen, IR equipment and scanning path;
- use of new heating and measuring technique;
- combining the TNDT with other NDT methods.

The first approach is nearly exhausted with procedures shown in *figure 2*. Some cute techniques, especially designed to suppress the surface noise, could be borrowed from IR pyrometry but they rarely fit the real TNDT tests.

We do not intend to describe here the history and parameters of modern heating and temperature measuring technique being able to refer the reader to bulky bibliography on this subject [25]. Special review of Russian IR imagers was done in [31]. Some rather interesting remarks about thermography as confusing term were recently reported by C.C.ROBERTS [32]. As for heating technique it is in practice limited with bulbs, lasers, air guns, electrical current and mechanical vibration [22-26].

More promising results could be obtained if to combine the thermal, optical, mechanical and ultrasonic tests.

Mirage effect (see *figure 2b*) proposed in 1979 differs from the common spot-by-spot scanning scheme by very sensitive temperature measuring device based on the deflection of a laser beam which is propagating close to surface (temperature resolution up to 10^{-8} °C). Thermal wave approach combined with mirage procedure provides the most sensitive technique as for defect sizing. It was succesfully used to distinguish delaminations, cracks and porosity at the depth up to 0.5 mm in carbon epoxy skin of aluminum combs. The same method was able to detect the defects by size 0.5 μm under the plasma sprayed coating [27].

Another example of joint use of thermal and optical effects is *photoacoustic microscopy by photodeformation* proposed in 1983 [33] and now used in micronic scale. Here the probing laser beam is directed onto the scanned area parallel to the heating laser beam (*figure 2c*). Surface deformation modulates the reflected beam. Optical, mechanical and thermal properties could be identified by measuring the amplitude and phase of signal.

Joint consideration of thermal and mechanical effects seems to be promising in getting new results on damage in composites. *Vibrothermography* involves the forced mechanical oscillations of a specimen while defect areas produce more thermal energy due to different dissipative and transformation mechanism. The flaws and other imperfections are seen as hotter spots. Method of *thermoelastic emission* is based on the thermoelastic equation which relates the small variations of

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temperature and stress. To specify this method the term *Stress Pattern Analysis by Thermal Emission* (*SPATE*) is often used with corresponding experimental equipment having the same name. High sensitivity of this method was achieved due to high temperature resolution of IR imager which was in its turn obtained by averaging the frames. Features of both methods are described in [34,35].

Since TNDT procedures are developing into the area of milliseconds time and millicentigrades temperature more and more similarity could be found between thermal and acoustic tests. In fact the hyperbolic heat transfer equation which is valid for explosive-like processes presumes the final speed of heat connected with phonons' propagation. On the other hand, the flux of phonons could be viewed as sound too. *Thermoacoustics* or *optoacoustics* which involves the flash laser heating and measurement of ultrasonic parameters is the new promising technique with high sensitivity to small structural variations.

9. Image processing techniques and new kinds of images

In IR TNDT it is possible to deal with a couple of images which we classify here for:

- images of directly and non-directly measured external parameters (IR radiation intensity, emissivity, heat exchange coefficients etc.);
- common thermograms and thermograms obtained by using the standard image processing technique (fitting, filtering, morphology processing etc.);
- images of properties of specimen or/and defect (specific heat transfer time, effusivity, diffusivity, thermal resistance, defect thickness, defect depth etc.).

It was already mentioned that IR equipment calibrated in temperature supplies the 3D file of data $T(x,y,\tau)$ which consists of plain thermograms. Standard image processing technique is pretty useful and nearly always necessary in order to subdue the noise and to make the image more operator-friendly. First of all it concerns the spatial filtration. Effect of filtration is illustrated by *figure 4.* Standard forth-and-back Fourier transformation provides usually the same results as common smoothing or median filters if it is not connected with special algorithms (see below). But segmentation, labelling and another elements of artificial intelligency proved to be quite useful although they are able to erase the prints of small defects. Morphology processing of thermal tomogram which allowed to suppress the artifacts around defects is shown in *figure 5.* Fitting technique was recently described by H.I.SYED *et al.* who performed least square fitting of temperature evolution data by polynomial functions in the following form [36]:

$$T(\tau_j) = \sum_{i=1}^{n} a_i f_i(\tau_j)$$

Many researchers noticed independently the positive role of the first and second spatial derivatives (i.e. in form of Laplacian $\nabla^2 T$) which underline the defects' edges and are sometimes able to find the defect on the unclear background. Unfortunately any derivating technique enhances the noise too.

The next step of our classification involves the images obtained if physical processes in specimen are taken into account.

The basic idea is to analyze the time evolution of each pixel in thermogram in comparison with pixel taken by an operator *a priori* as the non-defect one. In any TNDT procedure it allows to produce the ΔT_m *image* and τ_γ *image* called us as *timegram* (here γ specifies the relative temperature level and corresponding time point in the evolution curve of *figure 3a*). This transition from temperature domain to time domain seems to be very fruitful because the time parameters are more resistant to surface noise, i.e. noise of emissivity, which still limits the TNDT possibilities more than IR detector noise. Examples of these images are shown in *figure 6.*

Temperature-time history of IR images is used in the *zero-order temporal moment* technique based on the integrating excess temperature of a specimen over time [37]. It is known that after this operation the white noise is decreased by $\sqrt{N}$ times (N being the number of stored images) and the useful signal will increase. Moreover it was assumed that this temporal moment M is connected with specimen thickness L, defect depth l and resistance R by simple expression [37]:

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$$M = \int_0^\infty \Delta T(x,y,\tau)\mathrm{d}\tau = WR(1 - l/L)^2$$

Unexpectedely for thick samples the M value depends only on the thermal resistance of defect. It was reported that this method is sensitive to deep and small values of R.

The next obvious step is to calibrate the images mentioned above in some specimen's parameters. The ΔT_m image is usually calibrated in *thermal resistance* or *thickness* of defect. Timegrams could be calibrated in terms of thermal properties: *effusivity* in one-side and *diffusivity* in two-side procedure. The image of effusivity could be found in [37], diffusivity image in [38].

W.P.WINFREE and P.H.JAMES showed that in a specimen with high-conductive layer placed above low-conductive one the visibility of interface defects could be enhanced by producing the *heat flux image* for boundary layer. It was found that Laplacian of front-surface image corresponds to the flux pattern. So once more the validity of derivatives has been confirmed. Implementation of this method was done with special 2D filter which effectively suppressed the non-uniform heating and seemed to be useful for different specimens [39].

Algorithm of dynamic thermal tomography proposed by V.VAVILOV and V.SHIRYAEV in 1985 involves slicing the front-surface timegram by *isochrone* technique resulting in the particular *tomograms* which represent the distribution of specimen's thermal properties inside the chosen internal layer [40]. It means that timegram is calibrated in *defects' depth*. Examples of dynamic thermal tomograms are presented in *figure 7.* Algorithm of computerized axial tomography was described in 1986 by A.J.KASSAB and C.K.HSIE for steady-state inverse problem in order to determine the shape of specimen's rear surface [28]. Unfortunately this algorithm was not later spreaded onto sub-surface irregularities.

Cross-sectional timegrams obtained by cutting the 3D data parallepiped $T(x,y,\tau)$ with planes perpendicular to x or y axes are shown in *figure 8a,b* illustrating again the effect of morphology processing. It is possible to produce *cross-sectional tomograms* too (see *figure 8c,d*) by slicing the layers of width (or thickness) $\Delta\tau$ in the image of *figure 8a.*

Recently L.D.FAVRO *et al.* proposed the *inverse scattering* algorithm intended to reconstruct the distribution function of planar defect $f(x,y)$ [29]. Temperature signal $\Delta T(x,y,\tau)$ called by authors as *pulse-echo thermal wave image* was presented as convolution of two functions:

$$\Delta T(x,y,\tau) = \iint g(x-x', y-y', \tau)\, f(x',y')\, \mathrm{d}x'\mathrm{d}y'$$

where g is function derived from basic heat transfer solution with some modifications involving the defect depth. According to convolution feature the last expression means that in Fourier space we simply deal with multiplied functions. Consequently, if to divide the Fourier-image of ΔT by Fourier image of g and then make the reverse transition to real space we could obtain the f function. It seems that this rather simple treatment of common thermograms allows to define defects edges clearly not regarding their depth [29].

10. Decision making

Decision making algorithms are of special interest because TNDT method is more and more evolving into in-field and workshop technique. Unfortunately, up to now most of researchers limit themselves with single (usually - artificial) defects and do not report the statistical parameters of detection. It seems that we have to rely more upon the experience of operators than upon the artificial intelligence in spite of recent successes in this area [18]. Moreover the use of known statistical procedures (i.e. *Neumann-Pearson criterion*) requires the knowledge of noise. Some results have been reported in [23-27]. Here we limit ourselves with following remarks:

- any TNDT test is *noisy* ; everybody is aware of this but reliable statistical information about noise is still scarcely available; nevertheless, it was reported that even black paints do not provide the uniformity better than 2 % of contrast A [27];
- TNDT sensitivity when limited by temperature resolution only could be very high allowing to detect the smallest irregularities, e.g. as matrix breaks in composites; oppositely, the high decision making threshold guarantees only large defects to be detected;

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- when using the temperature point readout in the TNDT test the Neumann-Pearson criterion is recommended; for 2D colour or Black & White images evaluated by an operator the *Tanimoto criterion* was proposed [27].

11. Conclusion

Modern thermal NDT is the integrated scientific area where academic interests, R&D activity and industrial needs meet each other. I hope that more intensive than before the international cooperation of enthusiasts will help to avoid the undesirable research doubling and will open the new attractive fields.

Acknowledgments

The author would like to thank D.Balageas (ONERA, France), X.Maldague (University Laval, Canada) and E.Grinzato (ITEF, Italy) for their support and cooperation.

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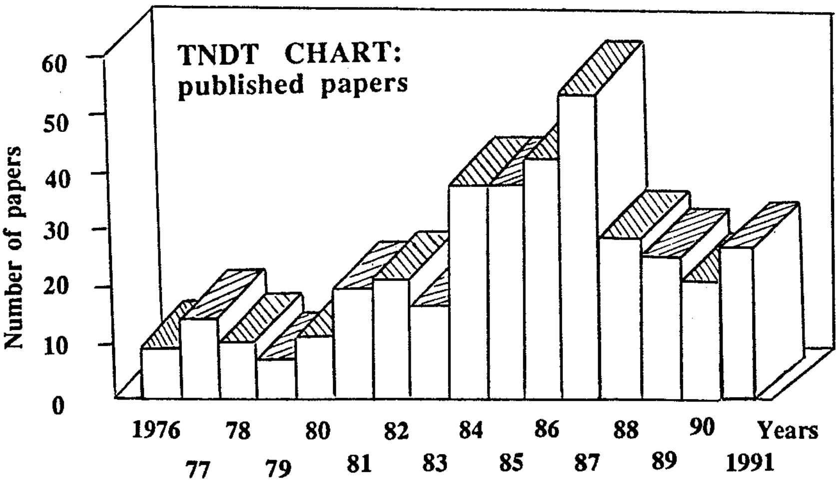

Fig.1. TNDT papers published in the international journals

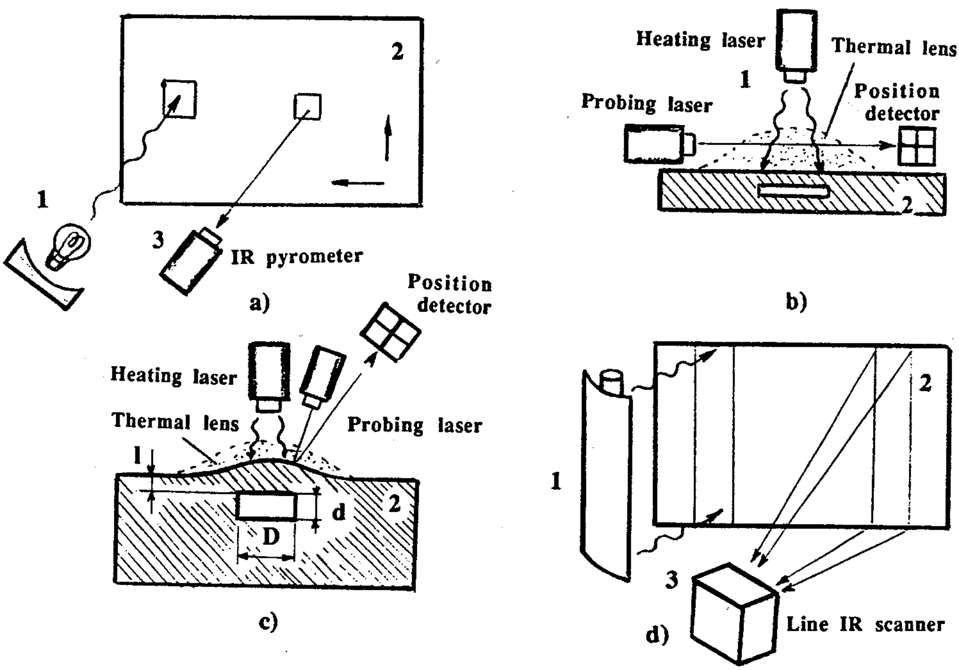

Fig.2. TNDT procedures (1-heater; 2-specimen; 3-IR device):

a - spot-by-spot scanning
b - "mirage" technique
c - "photoacoustic" by "photodeformation"
d - line scanning

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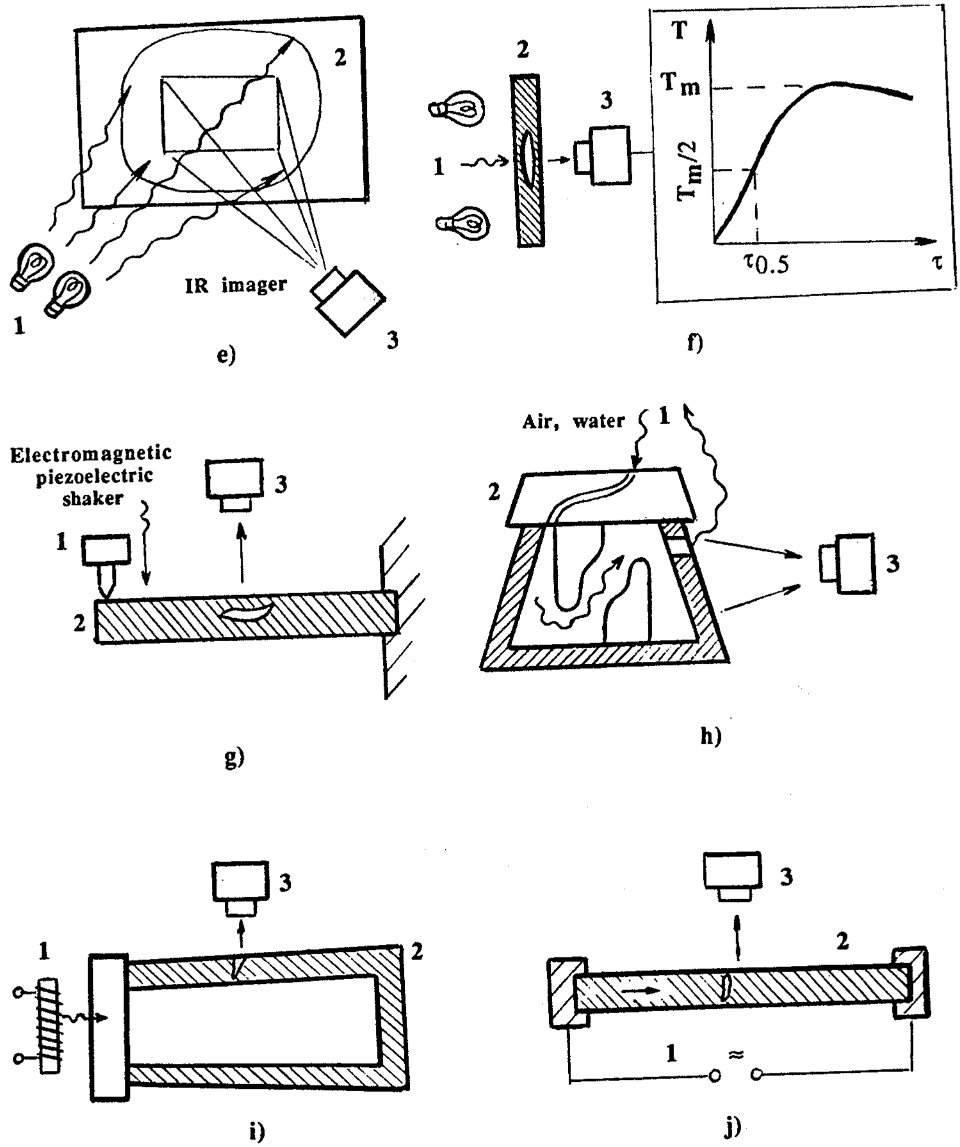

Fig.2 (continued). TNDT procedures:

e- thermography procedure
f-"flash" method
g-thermography with mechanical excitation of a specimen
h-thermography of blocked turbine blades
i -thermography of perpendicular-to-surface cracks in turbine blade
j -thermography of perpendicular-to-surface cracks by passing the electric current

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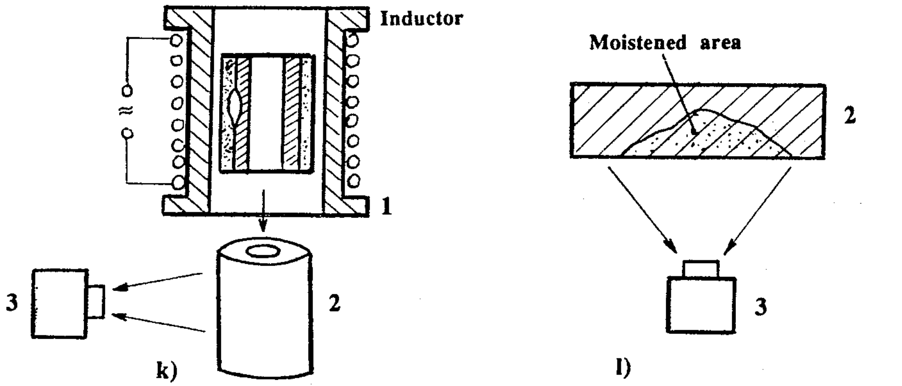

Fig.2 (continued). TNDT procedures:

k-inductive heating of non-metal-metal specimen
l- thermographic detection of moisture

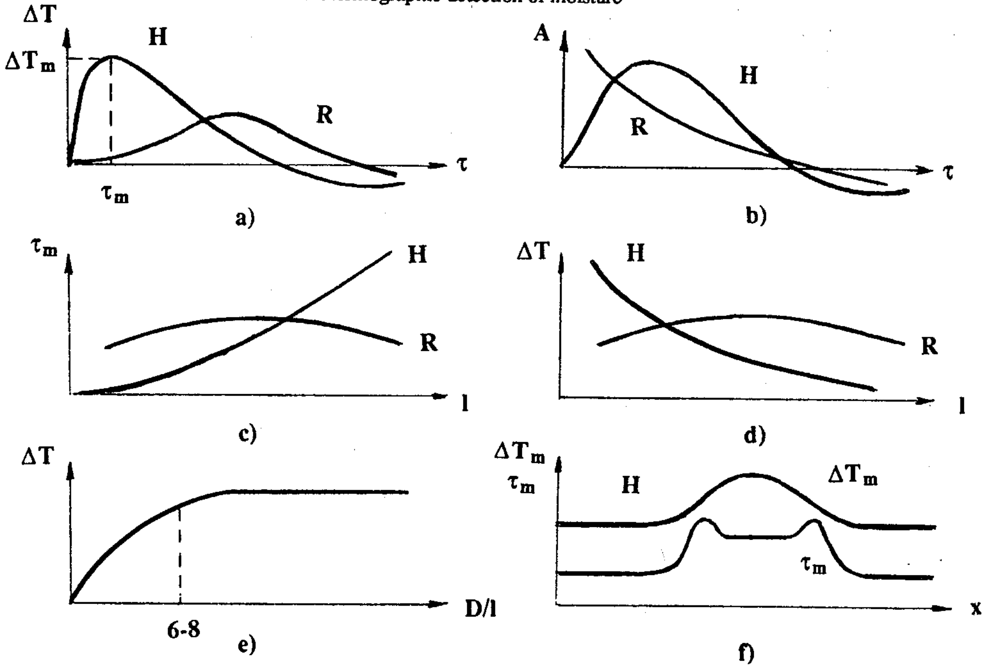

Fig.3. Qualitative TNDT features

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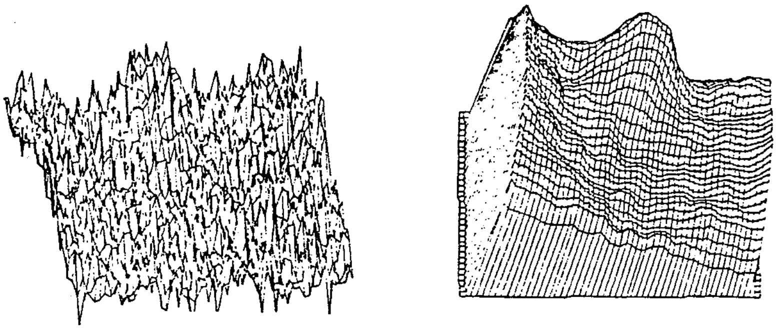
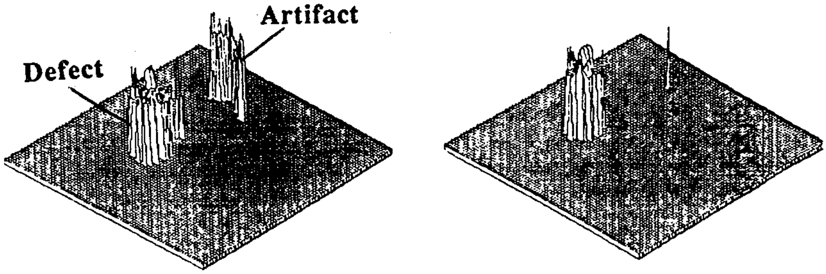


a - raw image

b- filtered image

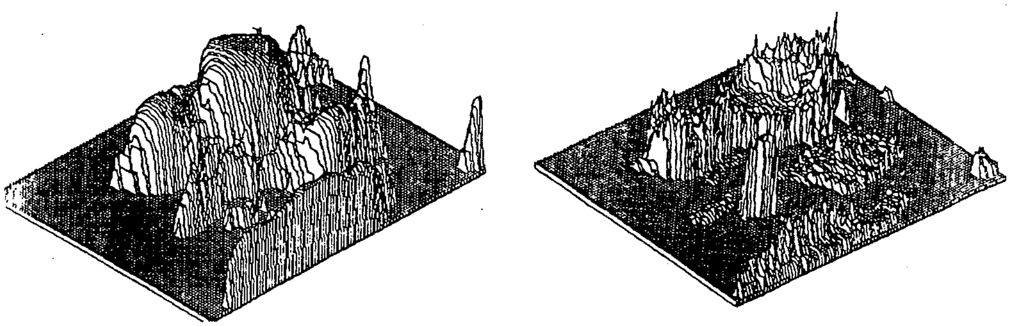
Fig.4. Filtering effect for the IR image of carbon fiber reinforced plastic with teflon insert (two smoothing filters 3x3 and 7x7):



a- before processing

b- after processing

Fig.5. Suppression of artifacts caused by enhanced edges of τ_m - distribution (tomogram of plastic with defects at the depth 3.6 mm):



a - ΔT_m - image

b - τ_m - image (timegram)

Fig.6. TNDT of plastic with defects at the depth from 1.8 to 5.4 mm:

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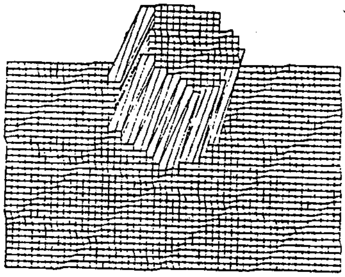
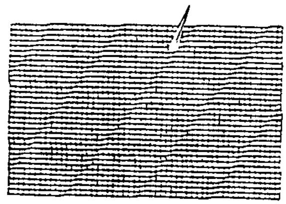


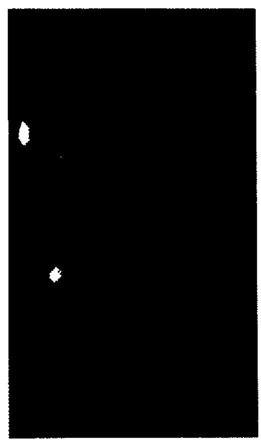
a - layer with insert



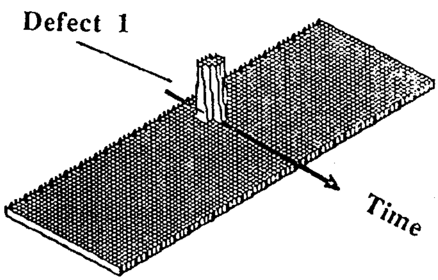
b - deeper layer

Fig.7. Thermal tomograms of carbon reinforced plastic with teflon inserts:

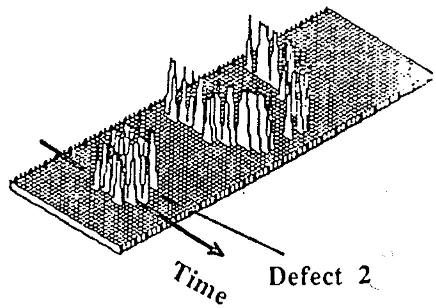
a - cross-sectional timegram for two defects at the depth 1.8 and 3.6 mm



b - after morphology



c - 3D presentation of cross-sectional tomogram for defect at the depth 1.8 mm



d - the same for defect at the depth 3.6 mm (note artifact from shallower defect)

Fig.8.Cross-sectional tomography of plastic with defects at depth 1.8-5.4 mm: