http://dx.doi.org/10.21611/qirt.2015.0007

Thermal NDT research at Tomsk Polytechnic University, Russia

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Abstract

The paper describes the history and the current status of research at Thermal NDT laboratory, Tomsk Polytechnic University, Russia. The emphasis is made on advanced modeling and data processing.

1. Introduction

In 1972, one of the authors (Vavilov) graduated from Tomsk Polytechnic University with a MS degree on thermal nondestructive testing (TNDT) and established the TNDT laboratory. Initially, the Tomsk research in this area was inspired by some published papers [1, 2] being mainly limited with theoretical investigations. Since that period of time, the modeling issues have become an essential part of the research; thus, the first paper published in 1973 introduced the approach which later became ubiquitous, namely, a temperature signal caused by a hidden defect is being calculated as a difference between the corresponding heat conduction solutions in the defect and non-defect areas [3]. As a result of the initial research, the importance of 2D and 3D numerical solutions became evident. The first deep analysis of 3D solutions was made by Vavilov and Taylor at Manchester University, UK, in 1982 [4]. It is interesting to note that, when solving multi-dimensional TNDT problems in that period, the computation time reached some minutes on the world most powerful CDC 7600 computer. A very similar research was done in parallel by MacLaughlin and Mirchandani in the USA [5]. It is worth mentioning that, in the 1970-1980s, the theory, hardware and methodology of TNDT were intensively developing by Carlomagno and Berardi [6], Busse [7], Balageas et al. [8], Maldague [9], Burleigh [10].

In the USSR, hardware development in the 1980s was related to the fact that the only foreign supplier of infrared (IR) cameras was AGA (later AGEMA), Sweden, and the cost of the equipment was too high to become a conventional research and/or industrial tool. A number of Soviet IR imagers (called in Russian “teplovisors”) were developed following three research directions: 1) copying Western equipment, 2) developing original concepts of IR vision, and 3) developing simplified versions of “teplovisors”. However, it was quickly understood that, for example, a temperature resolution of IR imagers is not a crucial factor in detecting and identifying subsurface defects (see the humorous TNDT laws suggested by the authors in Appendix).

By the end of the 1980s, i.e. at the eve of “perestroyka”, the staff of Tomsk laboratory of TNDT reached 25 employees, and the most of research was done for military and space applications. In that time, the Tomsk laboratory was developing a concept for the remote evaluation of water content in tiles of Buran space shuttle thermal protection. Two examples of home-made equipment developed at that period of time are shown in figure 1.

The period from 1990 to 2010 was marked by intensive international collaboration of Tomsk Thermal NDT laboratory with many known TNDT experts/teams: Maldague (Canada) [11], Grinzato, Bison and Marinetti (Italy) [12], Thomas et al., Burleigh (USA) [13, 14], Lahiri et al. (India) [15], Guo Xingwang (China) [16], Swiderski (Poland) [17], Kauppinen (Finland) [18].

2. Current status

A summary of current TNDT research at Tomsk Polytechnic University is presented in table 1.

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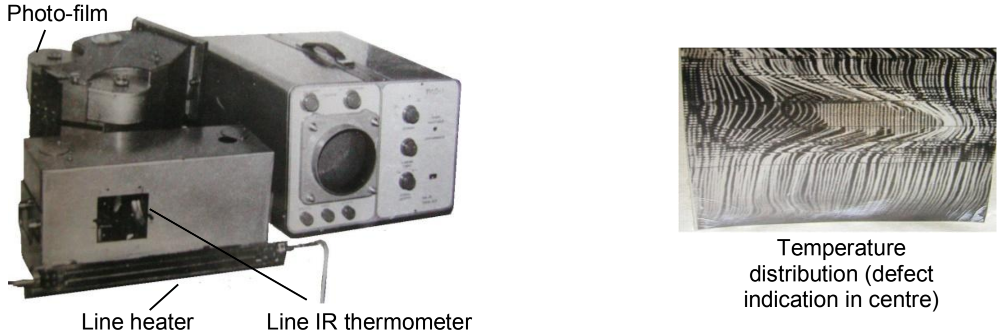
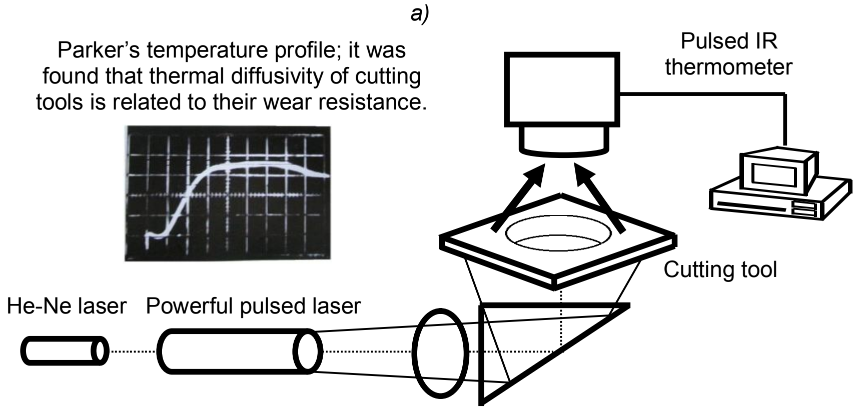


a)

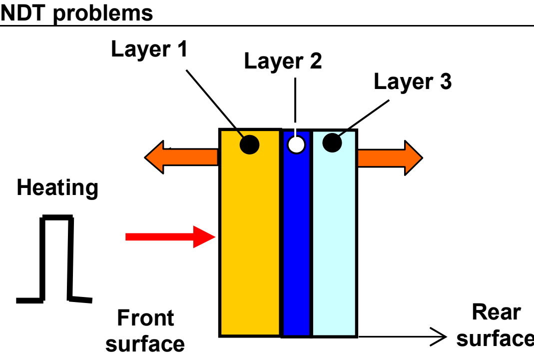


b)

Fig. 1. *Specialized TNDT equipment, Tomsk Polytechnic University:*

a – photo-recording IR device for active TNDT of soldered joints in large-size two-layer metallic cylinders (1980),
b – TNDT device for inspecting cement carbide cutting tools (1994)

Table 1. *Thermal NDT research at Tomsk Polytechnic University*

Research area description	Illustration
Modeling TNDT problems	
Multilayer is a basic program for analytical modeling heat conduction in 3-layer plates, where the central layer can represent either a bonding structure, or a defect (laterally-extended defects are assumed). The difference between the corresponding solutions as a function of time is a result of calculation. Program has been used for verification of 2D and 3D numerical solutions.	

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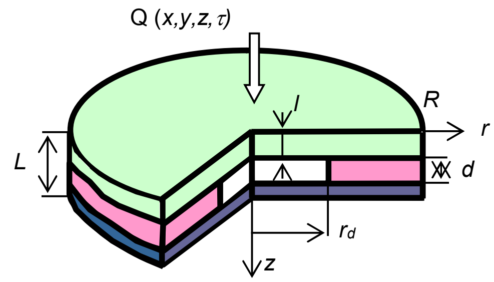
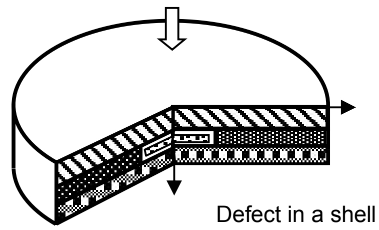
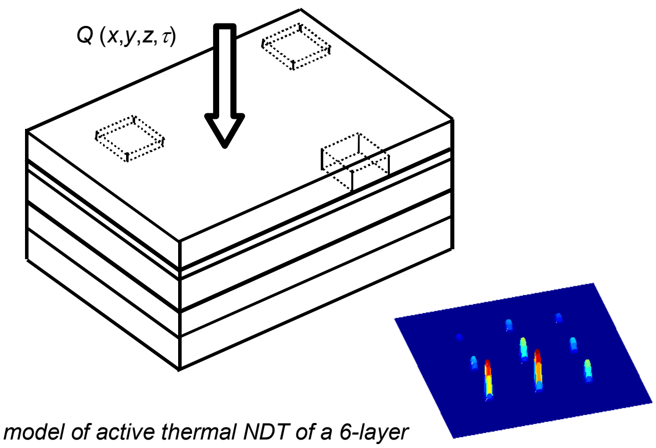
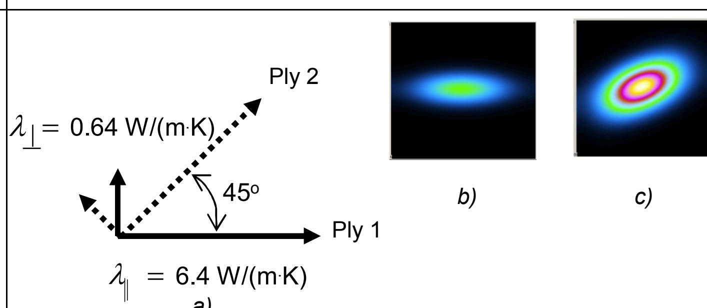
ThermoCalc-2D is a basic program for the numerical modeling 2D heat conduction in 3-layer disks with disk-like defects (cylindrical coordinates) uniformly heated on the surface. Calculation results are presented as temperature evolution profiles in time and space with the automatic determination of maximum temperature signals and times of their appearance. Simple, accurate and robust.	
ThermoCalc-2DM is a version of ThermoCalc-2D, but a disk-like defect can be placed in a shell made of a different material, thus modeling, for example, a landmine in soil surrounded by thin air gaps, or a Teflon insert in a composite surrounded by modified host material.	
ThermoCalc-2D Build is a version of ThermoCalc-2D intended for building applications. It allows defining an arbitrary heating function and calculating both temperatures and heat fluxes density.	
ThermoCalc-6L is a basic program for modeling 3D heat conduction in a parallelepiped-like 6-layer body which might contain up to 9 subsurface defects (Cartesian coordinates). The 3D non-adiabatic anisotropic problem is being numerically solved by using an implicit finite-difference method. External sample heating can be modeled with a uniform, Gaussian or spatially-arbitrary heat flux (in the last case, an experimental or calculated heat mask is being used). Calculation results are represented by 2D time-dependent temperature distributions on the sample surfaces or inside the sample. The Program calculates time evolution temperature profiles and determines maximum signals and times of their appearance. The results can be saved as IR image sequences or Matlab 3D vectors. The Program allows modeling complicated defects.	*The model of active thermal NDT of a 6-layer plate with subsurface defects subjected to external heating. A calculated temperature distribution can be saved as an image sequence or Matlab matrix.*
ThermoCalc-36L is a version of ThermoCalc-6L but the number of sample anisotropic layers can reach 36. Each subsequent layer can be tilted against the previous one by a certain spatial angle, thus modeling composites with anisotropic layup of fibers.	*Under spot-like heating, the anisotropy of a composite with 45° fiber layup (a) is clearly seen in one-layer (b) and two-layer (c) samples*

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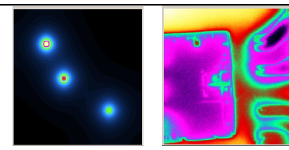
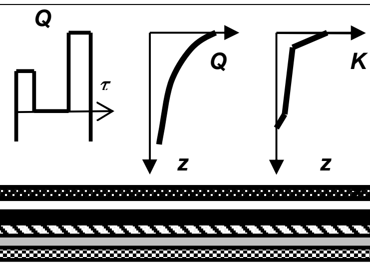
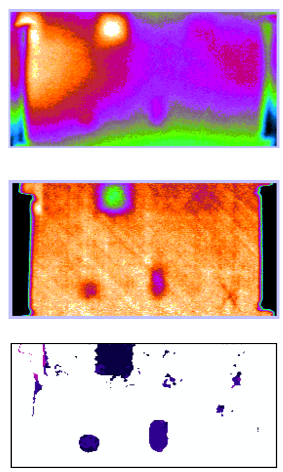
<table>
<tr>
<td>ThermoCalc Source is a version of ThermoCalc-6L but each of 9 defects simulates a heat source with a particular volumic heat power. The Program was designed for modeling defects in micro-chips and can be used for evaluating power generated by cracks under ultrasonic stimulation.
Both additive and multiplicative noise can be imposed onto calculated temperature.</td>
<td>
a) b)
Three heat sources in a chip with no noise (a) and with imposed real-chip emissivity noise (b)</td>
</tr>
<tr>
<td>ThermoCalc Mine is a version of ThermoCalc-6L but it allows modeling: 1) arbitrary heating function in time, 2) exponential absorption of heating energy in a tested material, 3) linear variation of thermal conductivity across layer thickness. Program was primarily developed to model the detection of landmines in moist soil under solar irradiation.</td>
<td>

A heating function time profile Q(τ) is defined in table form. Heating energy Q(z is exponentially decaying with depth. Material thermal conductivity K(z) varies linearly with depth.</td>
</tr>
<tr>
<td colspan="2">Processing experimental data</td>
</tr>
<tr>
<td>ThermoFit Pro is the Program dedicated to off-line advanced treatment of both experimental and artificial IR images. The Program implements the most of world achievements in TNDT data processing.
The main processing algorithms are as follows: 1) filtration in time and space, 2) sequence normalization in order to suppress multiplicative noise, 3) suppression of additive noise, e.g. conditioned by reflections, 4) polynomial fitting of time evolutions, 5) Fourier time analysis; obtaining phasegrams and ampligrams produced at particular Fourier frequencies, 6) wavelet time analysis, both scalar and complex, 7) principal component analysis (PCA).
The Program implements some unique processing algorithms, namely, thermal tomography, 2) 1D defect characterization (to evaluate defect depth and thickness); 3) 3D defect characterization (this technique takes into account visible lateral size of defects); 4) determination of material thermal properties, both effusivity and diffusivity, 5) statistical analysis; determining signal-to-noise ratio, 6) corrosion characterization.</td>
<td>
a)
b)
c)
Data processing examples in TNDT of CFRP composite: a-source image, b- Fourier phasegram, c-thermal tomogram of the 1.1-1.3 mm layer</td>
</tr>
</table>

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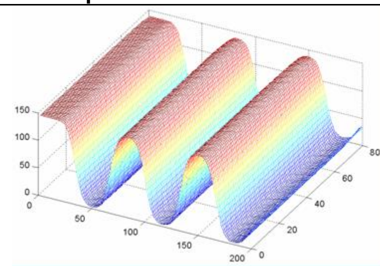
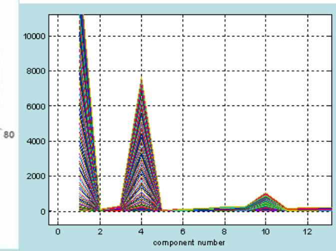
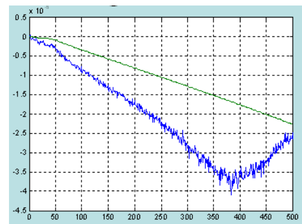
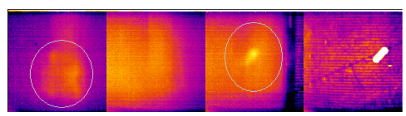
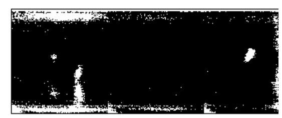
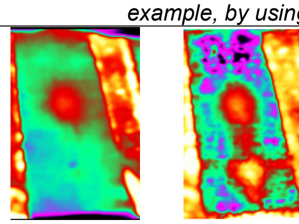
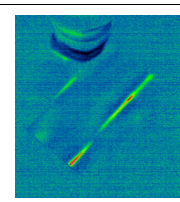
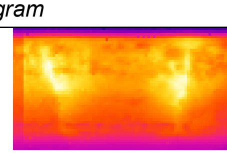
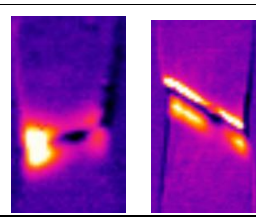
New experimental procedures in active TNDT	
Determining material anisotropic thermal properties In a two-sided test procedure, a modified Parker technique is used for determining three components of thermal diffusivity $\{\alpha_x, \alpha_y, \alpha_z\}$. A one-sided procedure is recommended for the determination of lateral components of diffusivity $\{\alpha_x, \alpha_y\}$ and thermal effusivity $e_z = \sqrt{C\rho\lambda_z}$. To stimulate a test material, one may use lasers and lamp heaters in combination with a spot or slit mask.	 *a)*  *b)*  *c)* *Anisotropic composite is heated through a slit-mask (a), afterwards, the Fourier spectrum is being analyzed at the carrier frequency (b). Thermal diffusivity is determined by each spatial coordinate by the slope of the straight line that is the evolution of the logarithmic "Fourier-temperature" in time (c)*
Evaluating rear-surface corrosion Both the method and the experimental set-up are developed to evaluate rear-surface corrosion quantitatively.	  *A cylindrical sample is sequentially monitored, afterwards, a composite IR thermogram (left) is converted into a binary image (right), for example, by using a neural network.*
Ultrasonic IR thermography Ultrasonic stimulation is performed at the frequency of 22 kHz. The indentor electrical power is up to 2.5 kW and the duration of stimulation is from 0.1 to 10 s. A defect-free material remains cold, while structural inhomogeneities, in particular, surface and subsurface cracks, generate thermal energy due to internal friction and plastic deformation. This method is applicable to both metals and non-metals.	 *Inspecting quality of friction stir welding of aluminum, some defects are clearly detected: left-source image, right- wavelet phasegram*  *Extended cracks in composite*
Induction IR thermography This technique has been applied to the detection of fatigue cracks in thick steel samples. The heating is accomplished inductively with the eddy current frequency being up to 30 kHz and the inductor power up to 30 kW.	 *Two fatigue cracks are clearly seen in the IR thermogram of a rail which is moving through an inductor*
Material fracture analysis Samples under standard mechanical tests are thermographically monitored with simultaneous acquisition of IR image sequences. The goal of analysis is to predict destruction and evaluate life source of (nano-) materials.	 *A polycrystallic titanium reveals a single powerful source of thermal energy appearing in the damage area (left), while nanotitanium is characterized by uniform temperature increase across a whole cross-section of damage (right)*

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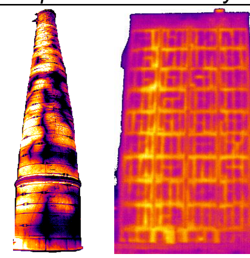
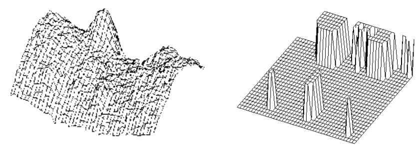
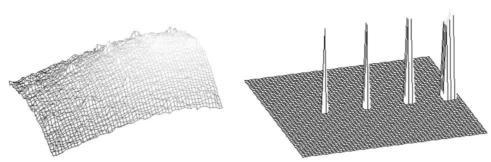
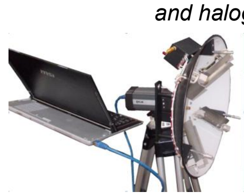
<table>
<tr><td><u>Detecting water ingress in aircraft under exploitation</u>

A technology of remote water detection in composite honeycomb panels of aircraft under exploitation is proposed. Several Russian-made Toupolev-204 airplanes have been inspected. A combination of ultrasonic and IR thermographic methods is under development to evaluate water content quantitatively.</td><td>
Water is clearly seen in ailerons, elevators and other airplane panels immediately after landing</td></tr>
<tr><td><u>IR thermographic diagnostics in power production and building</u>

A great deal of practical experience is acquired on energy audit of buildings, inspection of boilers and chimneys, etc.
Some federal normative documents and inspection guidelines have been developed.</td><td>
Typical defects in chimneys (left) and residential buildings (right)</td></tr>
<tr><td colspan="2">Data processing algorithms in active thermal NDT</td></tr>
<tr><td>Many data processing algorithms developed worldwide are included as standard options in the ThermoFit Pro computer program (see above). Some novel algorithms are under development to ensure suppression of noise and enhancement of signal-to-noise ratio. The unique algorithms are: dynamic thermal tomography, 3D normalization, correlation analysis and defect characterization.</td><td>
Inspection of CFRP composite: left-source image, right-after treatment with a neural network


TNDT of CFRP composite: dynamic thermal tomography allows to underline defects in a particular layer</td></tr>
<tr><td colspan="2">TNDT hardware</td></tr>
<tr><td>FLIR SC 7700M, ThermaCAM P65, NEC TH-9100, FLIR A325 and Testo 875 IR imagers are available. For heating, continuous and pulsed optical sources and air blowers with power up to 30 kW (3 kJ) are used.</td><td>
Two implementations of a unit intended for the detection of hidden corrosion in metallic cylinders by using Xenon flash tubes (left) and halogen lamps (right)


IR thermographic unit for inspecting aircraft</td></tr>
</table>

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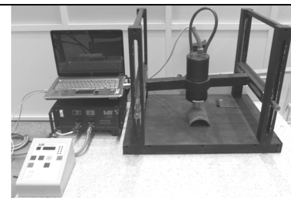
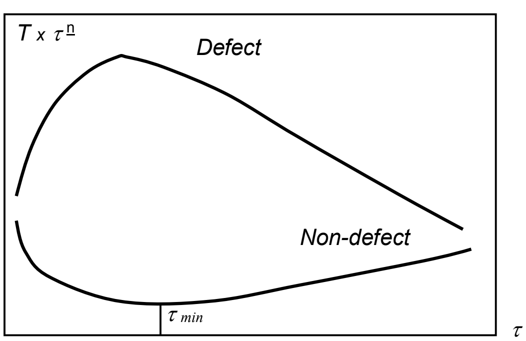
Set-up for ultrasonic IR thermographic NDT A specialized source for pulsed ultrasonic stimulation by using a magnetotostrictive indentor has been developed (ultrasonic frequency 22 kHz with ±120 Hz deviation, pulse duration 0.1-10 s, electrical power up to 2.5 kW).		*Set-up for ultrasonic IR thermographic NDT*

3. Perspective research

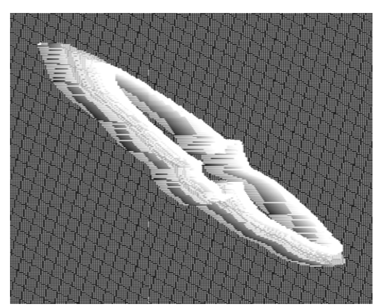
In TNDT modeling, a current trend is the development of a flexible and user-friendly software package which would allow solving typical 3D TNDT problems when involving non-adiabatic (linear and non-linear) heat exchange, arbitrary heating, dependence of thermal properties on space and time, phase transformation of substances, etc.

In data processing, the emphasis will be done on the development of inverse algorithms which are to be accurate, robust and applied to all pixels in image sequences thus enabling to produce images of defect depth and thickness. Some novel approaches suggested by the Tomsk team, such as dynamic thermal tomography and one-sided determination of thermal diffusivity, will be further explored. Thermal tomography, unlike classical thermography, is a technique which enables slicing a solid by few layers due to fact that deeper layers produce front-surface signals with increasing time delay [19]. Another novel idea is to determine material diffusivity in a one-sided test by using formulas similar to Parker's one [20]. The concept is to produce an artificial function $T(\tau)\times\tau^n$ in each pixel, where τ is the time, and *n* is typically from 0.01 to 0.5. In non-defect areas, the time evolution of this function reveals a clear minimum $\tau_{\min}$ (figure 2a) where thermal diffusivity can be calculated by the expression: $a = Fo_{\min} L^2 / \tau_{\min}$, where $Fo_{\min}$ is a function of *n*; for instance, $Fo_{\min}$ =0.2237 for *n*=0.4 that seems to be an optimal value when determining diffusivity [20]. Over subsurface defects, the $T(\tau)\times\tau^n$ function behaves in a more complicated way but often reveals clear maximums, as shown in figure 2a. This fact can be used for developing reference-free thermal tomography (see the thermal tomogram of impact damage in CFRP in figure 2b).

Another novel research direction is the evaluation of the quality of the so-called hyper-conductive modules, or mini heat tubes (figure 3a), used for heat dumping from satellite electronic units. These modules represent a hermetic multilayer construction filled with a liquid heat carrier. Heat transfer occurs due to heat carrier phase transformation. The equivalent thermal conductivity of mini heat tubes may reach 25000 $Wm^{-1}K^{-1}$, and their efficiency depends on the uniformity of their structure. In our preliminary research, mini heat tubes were heated with a flash Xenon tube while the sample rear surface was monitored with a FLIR SC7700 IR imager (acquisition frequency 412 Hz). By converting a sequence of source IR thermograms (figure 3b) into a map of diffusivity (figure 3c), one may efficiently evaluate the characteristics of heat conduction within mini heat tubes (note a very high diffusivity values compared to 'normal' solids, both metals and non-metals).



a)



b)

Fig. 2. $T(\tau)\times\tau^n$ *concept: a) evolution in time, b) reference-free thermal tomogram of impact damage in CFRP*

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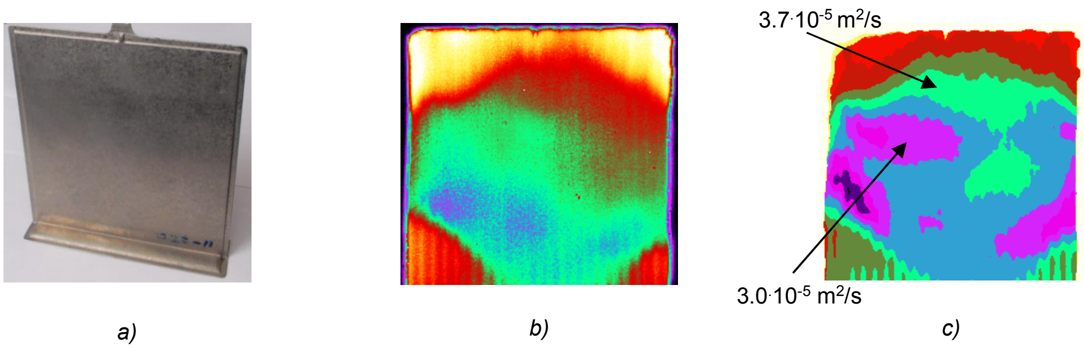

Fig. 3. *Pulsed IR thermographic inspection of mini heat tubes: a – mini heat tube, b – best source image, c – diffusivity map*

Perspective hardware development will involve Western-made components, in particular, IR cores combined with compact heaters thus resulting in a portable TNDT unit, similar to the equipment supplied by Thermal Wave Imaging, Automation Technology, Thermosensorik, Edevis and some other world manufacturers. A key point is supposed to be suppression of additive/multiplicative noise which limits TNDT potentials. The scheme of a thermal tomographic unit which is currently in use is shown in figure 4.

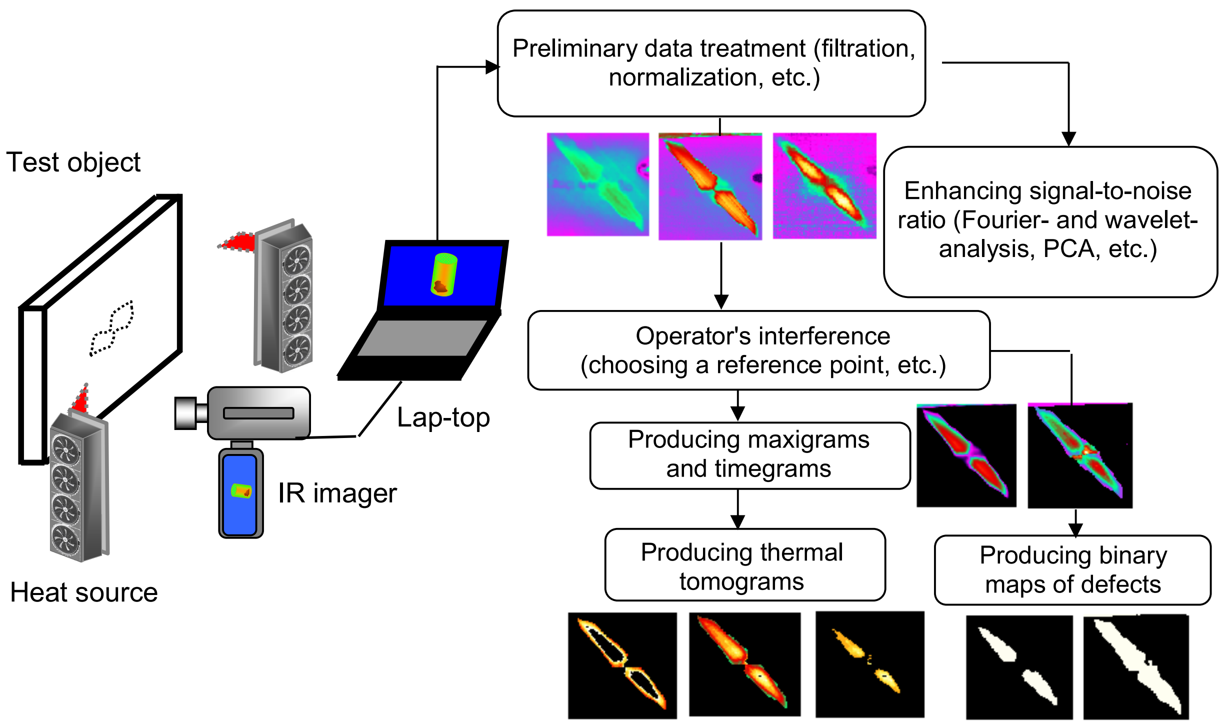

Fig. 4. *Thermal tomographic unit for inspecting composites*

4. Acknowledgement

Since 2014, TNDT research at Tomsk Polytechnic University is being supported by NIR # 445 (ONG), State order of the Russian Ministry of Higher Education for 2014-2016.

http://dx.doi.org/10.21611/qirt.2015.0007

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Appendix. *Thermal NDT laws prompted by long-lasting practice*

Law #1. Any data processing corrupts original data.
Consequence. Any data treatment should be avoided.

Law #2. Defects which appear as noise should be treated as noise.
Consequence. Most of defects will remain undetected.

Law #3. The universal noise constant is 0.1 ^{o}C.
Consequence. IR imagers having temperature resolution better than 0.1 ^{o}C will not provide better TNDT results.