THERMAL NON-DESTRUCTIVE TESTING: SHORT HISTORY, STATE-OF-THE-ART AND TRENDS

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Short history of infrared (IR) thermography and thermal/IR testing. In the scientific literature, the credit to the discovery of IR energy in 1800 is paid to Sir William Herschel who was a royal astronomer for King George III. The existence of invisible thermal rays had been hypothesized by Titus Lukretius Carus (c. 99-c. 55 BCE), a Roman poet and the author of the philosophic epic "De Rerum Natura" ("On the Nature of the Universe"). In 1696, Della Porta, an Italian observer, noted that when a candle was lit and placed before a large silver bowl in a church, he could sense the heat on his face. Hoffmann appears to have been the first who collected the invisible heat of a stove into a focus by the reflection of one or more concave mirrors. Afterwards, in 1770, Pictet, a French scientist, published the description of his famous experiment on focusing heat and cold. Well before Hershel's research Lomonosov, a founder of the Russian science, had been working on the problem of night vision. In 1758, Lomonosov invented a night vision telescope (*tubo nyctoptico*), and in 1762 he developed a mirror with high reflectivity. In 1829, Nobili proposed the first thermocouple based on the thermoelectrical effect which was discovered by Seebeck in 1821. A prototype of IR imagers was an evaporograph proposed by John Hershel, William's only son, who focused with a lens solar radiation onto a suspension of carbon particles in alcohol. It is remarkable that in 1840 J.Hershel called a thermal image "thermogram", the term still in use today. The second birth of thermal sciences dates back to 1900 thanks to fundamental studies of Planck, Einstein, Kirchhoff, Golitzyn, Wien and others, from one hand, and due to quick progress in IR detector technology, on the other hand. The first Russian experiments on the IR detection of warships were fulfilled by Pokrovsky et al. in 1927. By 1934, the Russian coastal IR systems were developed where the focusing optics reached a diameter of 1.5 m. Before the Second World War, systematic studies of semiconductor IR detectors began. It is often believed that a real prototype of an airborne opto-mechanical IR imager was developed by Barnes, USA, in 1954. This unit initiated the development of Forward Looking Infrared (FLIR) systems mounted on aircraft. FLIR systems employed only line scanning because the frame scan was performed due to airplane movement. The first portable IR imagers using linear cooled detectors on the basis of lead selenide (PbSe) were tested in the USA in the 1960s and then commercially manufactured as AN/PAS systems. For example, an *imaging* system AN/PAS 110 used a linear PbSe IR detector (2-5 μm wavelength band) and an oscillating mirror as a scanner, thus providing the frame frequency of 30 Hz and the temperature resolution of 0.1^{o}C. This model was of 10 kg weight and included a belt with batteries. Primary applications were in technical diagnostics and coastguard. In the USSR, in 1961 Miroshnikov demonstrated a thermal trace of a person lying on a wooden floor which was keeping for 30 minutes after the person left. Even the person contour was detectable due to the unique (0.03^{o}C) for those years temperature sensitivity of the IR thermometer. The energy crisis of the 1970s ensured a state support to two Swedish companies AGA (now FLIR Systems) and Bofors which released on the market the first portable *IR radiometers* in the design which became widely-recognized for many next years. From 1970 to 1990, the progress in civilian applications of IR thermography chiefly owed to the activity of AGA (later AGEMA Infrared Systems, now FLIR Systems). In 1986, this company refused using liquid nitrogen and introduced a thermoelectric cooler, as well as a built-in processor for calculating true temperatures in a real time, into a Thermovision 870 model. In 1988, a Thermovision 400 model was marketed. Weighing 7 kg, this IR imager was remaining unsurpassed in outdoor applications for many years.

In the late 1980s, the US military released the Focal Plane Array (FPA) technology into the commercial marketplace. In 1995, AGEMA Infrared Systems began to produce IR imagers of a new generation (Thermovision-500) implementing FPA IR detectors. A US company Inframetrics invented a miniature Stirling cooler which was able to cool down IR detectors up to -200^{o}C. IR imagers of the 500th (later – 600th) series and, finally, cameras using Quantum Well IR Photodetectors (QWIP) commemorated the appearance of "IR vision" as it has been anticipated by the analogy with standard TV.

In general, the world market has undergone serious changes for the last decade conditioned by the finish of the Cold War and introduction of a new generation of IR detectors (FPA). Many modern IR cameras can be regarded as a dual-use equipment equally convenient for both military and civilian applications.

Thermal non-destructive testing (TNDT) is a particular application area of IR thermography with its own history. One of the first industrial applications of TNDT was related to analysis of hot rolled metal (Nichols, 1935). Contemporary analysis of material thermal properties goes back to the work by Vernotte devoted to the determination of human skin properties (1937). In the 1960s, IR thermography began to be used in the inspection of electrical installations and radio electronic components, thanks to the appearance on the market of radiometric IR imagers from AGA, Sweden. One of the first implementations of the active TNDT process proposed by Beller in 1965 was the inspection of Polaris rocket motor cases; the heat pulse was accomplished by moving them into an area having a higher temperature. In that same period, Green performed a basic research on active testing of nuclear reactor fuel elements where special attention was paid to notorious emissivity problem. In the 1960s, TNDT attracted the attention of aerospace researchers during the space race and the American Society for Nondestructive Testing (ASNT) established an active IR committee and even published its own transactions.

By the end of the 1970s, applications of TNDT were still rather qualitative thus preventing the successful competition of this method with other inspection techniques. A new level of TNDT was achieved after the wider use of elements of the heat conduction theory, of which basics were summarized in the well-known books by Carslaw and Jaeger and Luikov. A "thermophysical" approach to TNDT has been extensively developed by Balageas, Vavilov and Taylor, MacLaughlin and Mirchandani, Popov and Karpelson and some other authors who introduced one- (1D), two- (2D) and three-dimensional (3D) models of defects in the 1980s.

In condition monitoring and predictive maintenance, IR diagnostics has been considered for many years as a reliable tool of indisputable economical benefit. But interest in TNDT has been "up and down". A new interest to TNDT which we witnessed in the last decade has been stipulated by the appearance of the second generation of IR imagers and a dramatic increase in computer processing.

Modern IR imagers. Nowadays, IR thermographic diagnostics and TNDT represent a mature high-technology field which combines achievements in the understanding of heat conduction, material science, IR technology and computer data processing. The high interest in the IR/thermal inspection technique is related to its universal character, high testing productivity and in-service safety.

The general information about world producers of IR imagers can be found in Web: www.directindustry.com. Leading world producers apply a flexible price politics to make IR imagers strongly dependent on system basic components and added accessories, mainly, lenses, filters and software. Very approximately it can be assumed that ex work price for basic imaging systems of a higher level may be from US$10,0K to US$15,0K. Radiometric systems of camcorder design may be in the range from US$35,0K to US$70,0K, and the price of specialized models, e.g. mounted on gyro-platforms of flying vehicles, may exceed US$150,0 K. Recently, some economic models appeared on the market, i.e. InfraCAM and i5 from FLIR Systems, Ti 30 from Fluke, MobIR-3,4,7,8 from Land/Guide and others by ex work price from US$3,0K to US$14,0K. It is important that, due to intensive competition on the world market, IR imagers of the same class but from different manufacturers are characterized by close prices which also depend on accessory availability and a level of servicing in a particular country.

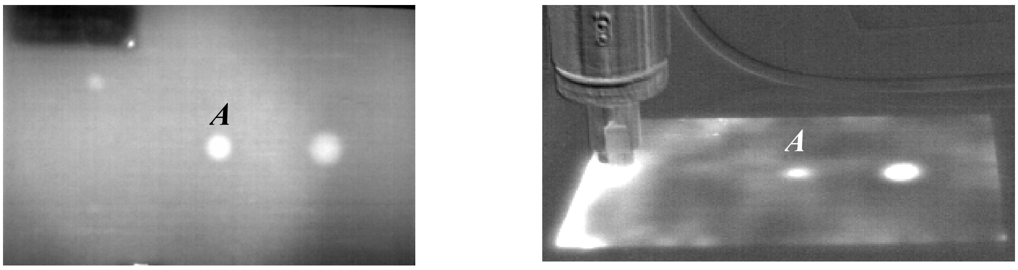
Modern IR imaging systems of the second generation realize a module principle and use FPA detectors, both cooled and uncooled. Supplying an IR detector module with a lens converts it into what is called a "thermal module" (a core) which in turn becomes a non-radiometric IR imager being added with a monitor. The further introduction of a temperature-measurement function requires undertaking considerable technical efforts and represents a know-how of manufacturers.

All IR imagers can be classified by application areas as follows: 1) simple imaging units used for night vision in military, IR reconnaissance, search and rescue, observation, fire fighting etc., such as PalmIR-250 from Raytheon, Night Conqueror from Cincinnati Electronics etc. (in some cases such units can be used in technical diagnostics; 2) radiometric (temperature measuring) imagers used in technical diagnostics and nondestructive testing (general-purpose IR cameras and modules, such as ThermaCAM P60 and ThermoVision A40 from FLIR Systems, TH-9100 Pro from NEC Avio, Testo-880 from Testo etc.); 3) radiometric computerized IR thermographic systems mainly intended for scientific research and characterized by the highest temperature sensitivity and frame frequency, such as ThermaCAM SC 6000 from FLIR Systems and SC 7000 from FLIR-CEDIP. In the latter case, short thermal events in thin coatings and aluminum sheets can be effectively analyzed for detecting hidden defects.

<u>Sources of thermal stimulation.</u> Along with the technical performance of IR imagers, that is permanently improving, the progress in TNDT is adherently related to techniques of heating. Optical heating remains the most acceptable in many test procedures, in particular, where short powerful pulses are needed. Xenon flash tubes are typically used in this case. The main problem here is ensuring a maximum absorbed energy that requires using a bunch of tubes of which radiation is to be well-focused on sample surface.

In the last decade, two other heating techniques have been becoming popular in specific test cases. The first one is called ultrasonic “lock-in thermography”, or “sonic IR imaging”, or “thermosonics” (VibroIR and SonicIR terms are also used). This technique is a further development of earlier known vibrothermography being based on the fact that, under intensive ultrasonic (sonic) irradiation, internal friction of defect edges causes local overheating without changing temperature of the sound material. The research conducted at Stuttgart University (Germany), Lawrence Livermore National Laboratory and Wayne State University (U.S.A.) has shown that that ultrasonic thermal patterns are quite different from those appearing under optical heating; hence, they might bear additional useful information about material structural inhomogeneities. This statement is illustrated with IR images in Fig. 1. A pleasant feature of this stimulation method is its applicability to metallic samples of complicated shape where fatigue cracks can be detected without painting samples black.

Another new TNDT technique combines IR thermography and eddy current stimulation of metals that allows the detection of surface and near-to-surface cracks. Except metals, eddy current (induction) IR thermography is also applicable to graphite epoxy composites and C/C-SiC ceramics.



a) b)

Fig. 1. Comparison between optical (flash tube 3 kJ) and ultrasonic stimulation (22 kHz) of a 1 mm-thick graphite epoxy composite:

a – optical stimulation (maximum temperature signal over defect ***A*** 1.16°C, mean non-defect excess temperature 2.2°C, signal to noise ratio SNR=18,6, temperature contrast 53%),
b – ultrasonic stimulation (maximum temperature signal over defect ***A*** 2.1°C, mean non-defect excess temperature 0.6°C, signal to noise ratio SNR=32, temperature contrast 580%)

<u>Image processing in TNDT.</u> A strong credit to the improvement of TNDT performance should be paid to the growing potential of computer data processing. The standard processing of IR images is

not different from the processing of other types of images mainly including various types of data filtration. In active TNDT, the unique feature of IR image sequences is that they reflect the evolution of temperature in time which is different in defective and sound areas. There are many algorithms of processing dynamic signals, both standard and specialized, i.e. related to the mechanism of heat conduction. In TNDT, the most applicable are the following algorithms: 1) 'classical' optimal detection (choosing optimum observation times for detecting hidden defects), 2) 'early detection' concept (at short observation times, lateral heat diffusion is low and image quality is high), 3) data normalization that means division of images captured at different times in order to decrease the image non-uniformity caused by uneven heating, 4) Fourier analysis (1D Fourier transform is applied to temperature time evolution, thus enhancing minor differences between defective and sound areas; 2D Fourier transform is applied to surface coordinates to allow the determination of lateral diffusivity, 5) wavelet analysis as a certain analog of the Fourier transform; this technique allows not only localization of frequencies but also keeps temporal resolution (the wavelet analysis has proven to be so efficient in data compression and noise reduction that one talks about the 'wavelet revolution' occurred at the end of 1980s), 6) implementation of tomographic principles in TNDT (emission IR thermographic tomography, thermal wave tomography, microwave and dynamic thermal tomography); in TNDT of solids the dynamic thermal tomography, which involves both periodical and pulsed heating, has been used; 7) polynomial (or exponential) fitting of pixel-based temperature functions that allows to smooth noisy data and replace long image sequences with a set of few polynomial coefficients; in combination with logarithmic data presentation and derivative analysis, this algorithm has been effectively exploited by Thermal Wave Imaging, a leading producer of TNDT equipment implementing the principles of Synthetic Data Processing (SDP) and Thermographic Signal Reconstruction (TSR); a disadvantage of polynomial fitting is the loss of the 'physics' while dealing with polynomial coefficients, 8) principal component analysis which is becoming increasingly popular in general NDT, 9) the use of artificial intelligence elements, in particular, neuron networks which, being well trained, allow both defect detection and characterization.

An example of advanced data treatment by using the dynamic thermal tomography algorithm is presented in Fig. 2.

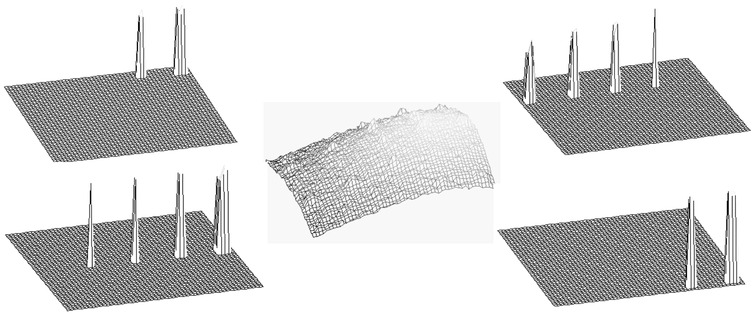


Fig. 2. Dynamic thermal tomography of a 1 mm-thick graphite epoxy sample (defects of different size at different depth, in centre – 'best' source image)

Applications. Following the words of Kriksounov '*Potentials of IR technology are limited only by our imagination*", it is impossible to describe all applications of IR thermography and TNDT even in a thick book. We shall limit ourselves with the trivial statement that IR thermographic technical diagnostics, including predictive maintenance, condition monitoring, as well as several aspects of night vision, has proven to be an established technique in industry and building. Perhaps, the inspection of electrical installations and building envelopes should be mentioned as well-established applications. In both areas, several national standards and guidelines are available in many countries, and some efforts are ongoing to establish international norms, merely to mention the ISO 9869-1998 standard "Thermal insulation -- Building elements -- In-situ measurement of thermal resistance and thermal transmittance" and the recent activity of the ISO Technical Committee to develop an international standard on the inspection of electrical installations.

In its turn, active TNDT of materials is a quickly growing NDT area, first of all, motivated by the broadening use of composites and surface-protected metals in aero space, power production and some other fields of cutting-edge technologies. TNDT allows the detection of such defects in the above-mentioned materials which can be hardly found by using more traditional NDT techniques; moreover, the unique test speed of TNDT allows the coverage of 100% of surface to be inspected that is very important in aero space. Therefore, TNDT strengthens its validity as a screening technique which forestalls using other NDT methods.

In aero space, the areas of primary use of TNDT are: 1) inspection of water ingress in honeycomb panels of exploited aircraft and porous high-temperature insulation of space shuttles, 2) detection of corrosion in aluminum aircraft panels, first of all, around rivets, 3) detection of defects, such as impact damage, in composites (boron epoxy patches, carbon- and glass-fiber reinforced plastics etc.) and honeycombs (delaminations, cell filling etc.), 4) general use of TNDT in the inspection of space shuttle structures on a launch pad and in outer space, 5) inspection of turbine blades (channel blockage, thermal-barrier protection defects and fatigue cracks). Many of the approaches above are also applicable to the inspection of boats made of composites.

Welding quality can be thermally checked in several ways. The observation of a welding process in infrared allows the optimization of welding process parameters. Welding joints can be checked for anomalies, such as pores, cracks and ‘kissing’ defects, which noticeably change joint thermal response. For example, portable units for the inspection of spot weld joints in the automotive industry are coming.

The TNDT use for the evaluation of corrosion in thick steel objects is under intensive discussion. The principles of this technique are well elaborated but the problem of the proper outdoor heating of thick metals is still expecting a practical solution. The same problem arises in the inspection of hot rolled metals in metallurgy. In general, some difficulties in the thermal inspection of unpainted ‘thick’ metals can be overcome by implementing new stimulation techniques, such as eddy current.

Also, there are many other areas of active TNDT applications which deserve a closer outlook, merely to mention the inspection of art objects, the detection of buried landmines etc.

<u>Trends.</u> Concerning the performance of IR imagers, a definite trend is further improvement of temperature and spatial resolution and increase of frame frequency. Such hardware will allow the inspection of both thin and thick high-conductive materials where excess temperatures and, hence, temperature signals in defect areas, are low. IR modules will probably become more efficient and practical to be a component of portable TNDT units with a flexible architecture (to allow both one- and two-sided access to test objects of plane, cylindrical and conical geometry).

A study of novel thermal stimulation techniques will be continued to improve their efficiency and decrease noise of a radiation nature. In some special cases, ultrasonic stimulation of structural inhomogeneities seems to be very attractive. A compromise between a maximum inputted energy and a possible destructive character of such stimulation should be achieved. In the case of metals, particularly, metallic rods and pipes, inductive heating may be a solution. Perhaps, lasers which presently are rarely used in practical TNDT could experience revival as powerful and flexible heat sources operating in a wavelength band aside spectral sensitivity of IR imagers.

Image processing will be as before forwarded to better recognizing subsurface defects on the clutter background. Fourier and principal component analysis which have successfully proven to be as the first-to-try techniques might be complemented with practical neuron networks. In parallel, more reliable defect characterization approaches will be developing, and the growing power of computers might allow a routine use of non-linear fit algorithms which will result in the simultaneous evaluation of some material and test procedure parameters, such as material thermal diffusivity, absorbed energy, heat exchange coefficient and others. Characterization algorithms should be essentially 3D to take into account a finite size of detected defects.

TNDT will probably confirm its role as a screening inspection technique but, if the problems stated above, will be successfully solved, thermal method may become unique in particular test cases. In parallel, the tendency to perform data fusion by analyzing results of some NDT techniques may be strengthening.