Active Infrared Thermography in Non-destructive Testing

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Abstract. *The contribution deals with state of the art non-destructive testing method – active infrared thermography. The method can be used for revealing of defects and inhomogenities inside the bodies, e.g. bubbles and cracks in materials, which can have crucial importance from the point of view of their physical-mechanical properties. Goal of the research is theoretical evaluation of the performance of the pulse active thermography as non-destructive testing method and its experimental validation.*

Keywords: temperature, emissivity, heat propagation, Finite Element Method, subsurface defect

1. Introduction

During the past years both passive and active infrared thermography have become powerful and effective tools in a wide range of applications, including science, medicine, industry and non-destructive testing. More common from these two methods is the passive IR thermography, where the thermal radiation emitted from object's surface (Planck's law) is scanned by infrared camera, and gives information about the surface temperature of the object in thermal equilibrium. On the contrary, by the active infrared thermography the object under test is thermally excited - usually irradiated by a source of infrared radiation. In this case the object is in non-equilibrium state and the transient temperature field measured by thermographic camera can provide information about the thermo-physical properties, defects and inhomogenities inside the object. Contemporary the main application fields of passive IR thermography can be found in civil engineering (inspection of thermal insulation of buildings), predictive maintenance (e.g. inspection of pumps, motors, bearings and electric insulators), medicine (diagnosis of diseases), agriculture and in a variety of research experiments. The active thermography is mainly used in non-destructive testing to reveal defect (e.g. bubbles, cracks) inside various materials and objects without harming them.

2. Pulse active infrared thermography

There are several techniques used in the active thermography, the main of them are pulse thermography PT and modulated (lock-in) infrared thermography MT. Combination of these two approaches is pulse phase infrared thermography [1]. In the pulse thermography the object under test is during a limited time thermally excited by an infrared source of radiation (see Fig.1). Some part of the IR radiation incident on the object's surface is absorbed (depends on the emissivity of the surface) and transformed into a thermal energy, which propagates by thermal diffusion from surface to the inward of the object. The thermal energy propagation within the

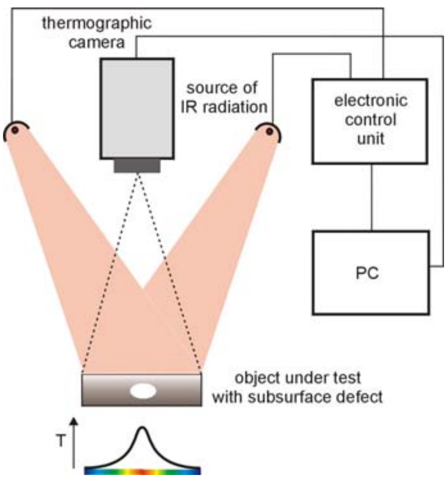

Fig.1 Basic set-up of active infrared thermography

material can be described by Fourier's partial differential equation

$$\rho.C_p \frac{\partial T}{\partial t} + \nabla.(-k.\nabla T) = Q \tag{1}$$

where T is temperature (K),
t is time (s),
Q is supplied thermal energy (J),
ρ is mass density of the material (kg.m^{-3}),
C_p is specific heat capacity of the material at constant pressure (J.kg^{-1}.K^{-1}),
k is thermal conductivity (W.m^{-1}.K^{-1}).

After the thermal excitation and in a simplified case (isotropic material), the Fourier's equation can be written as:

$$\frac{\partial T}{\partial t} = \alpha.\nabla^2 T \tag{2}$$

where

$$\alpha = \frac{k}{\rho.C_p} \tag{3}$$

is thermal diffusivity of the material (m^2.s^{-1}).

The principle of active infrared pulse thermography can be described as a measurement of time evolution of surface temperature differences, which arise as a result of different (e.g. reduced) thermal diffusion inward the object in places, where subsurface defects are present. In other words, subsurface defects change thermal diffusion rate, mathematically described by Fourier's equation (2), and therefore subsurface defects appear as surface areas of different temperature with respect to normal areas.

It is apparent that the thermal diffusion is not stationary and therefore exist some lower limit of observation time τ, when the effect (surface temperature differences) arise after thermal activation of the surface. This time is approximately equal to the time interval of the thermal pulse propagation from the surface to subsurface defect and can be estimated from the Fourier's equation [1]

$$\tau \approx \frac{z^2}{\alpha} \tag{4}$$

where z is depth of the subsurface defect.

For selected materials the estimated propagation times τ for depth of the subsurface defect z=5mm, together with other thermo physical constants, are introduced in the Tab. 1.

material	thermal conductivity k (W.m^{-1}.K^{-1})	mass density ρ (kg/m^3)	specific heat capacity C_p (J.kg^{-1}.K^{-1})	thermal diffusivity α (m^2.s^{-1})	propagation time for z=5mm τ (s)	emissivity 8-14 μm ε
aluminium	250	2700	870	1.06E-04	0.23	0.09
gypsum	0.47	1150	1090	3.75E-07	67	0.85-0.94
concrete	1.4	2000	1050	6.60E-07	38	0.85-0.94
epoxy	0.35	1300	970	2.78E-07	90	0.8

Tab.1 Estimated times of the heat pulse propagation to the subsurface defect with a depth 5mm.

3. Thermal modelling with the use of Finite Element Method

For the optimisation of the active IR thermography parameters (the amount of thermal excitation energy, duration of the pulse, observation time), and for the correct interpretation of the measured results it is necessary theoretically describe relevant thermo-physical processes running in the object, including absorption of incident thermal energy, propagation of the heat in the inhomogeneous environment with defects and thermal losses caused by conduction, convection and radiation to the surrounding. In very simple cases it is possible to find analytical solution of the problem, but in the real 3D complex objects it is necessary to use numerical solution of the Fourier's differential equation. One of the suitable methods is the finite element method – FEM [4]. The basic concept of this method is to divide the area of solution into smaller parts called finite elements, connected at nodal points (mesh generation). In each node the physical equilibrium equation is defined, and on the object's boundary the boundary conditions are defined. In this way the physical problem described by partial differential equation PDE is break down into linear system of equations. For thermal FEM simulation of active thermography method the Comsol Multiphysics program was used [4]. The geometry of the 3D object for simulation purposes was chosen as it is shown on Fig.2a,b.

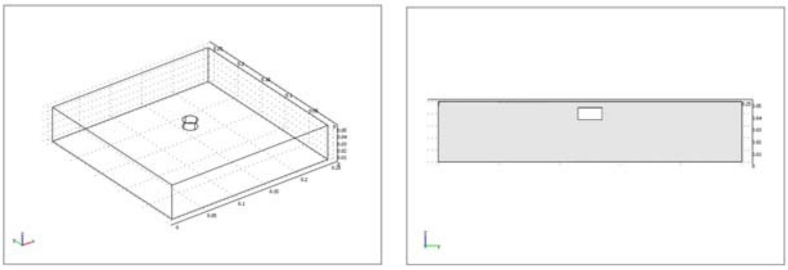

Fig. 2a,b Geometry of the object with subsurface defect

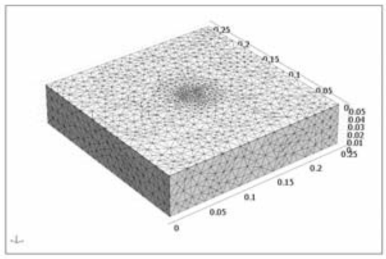

Fig. 2c Finite elements – 3D mesh

The generated mesh (see Fig 2.c). was created from 74843 tetrahedral finite elements

For the heat propagation model the PDE equation (1) was used with the following assumptions:

1. heat energy is exchanged between object and surrounding only through upper side of the object

2. upper side of the object is irradiated by the IR radiation flux 500 W.m^{-2}

3. the energy equilibrium through the upper side of the body is described by the border equation

$$-\mathbf{n}.(-k.\nabla T) = \varepsilon.\Phi + \varepsilon\sigma\left(T_s^{\,4} - T^4\right) + h(T_a - T) \qquad (5)$$

where T is temperature of the object,

T_s is temperature of the surrounding (background),

T_a is temperature of the air layer next to object,

ε is emissivity of the object's surface,

h is heat transfer coefficient (W.m^{-2}.K^{-1}).

As a result of model solving we obtain the transient temperature distribution on the object's surface with the geometry shown on the Fig.2, irradiated by the defined IR radiation. Model was solved for various materials (construction materials, metals, plastics, etc.), presented results bellow were obtained for construction material gypsum (see Fig. 3 and Fig.4).

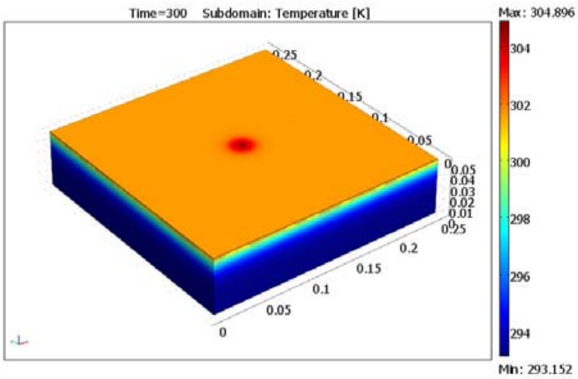

Fig. 3 Temperature field of the object with subsurface defect irradiated by IR radiation – pseudo-colour presentation of FEM model results

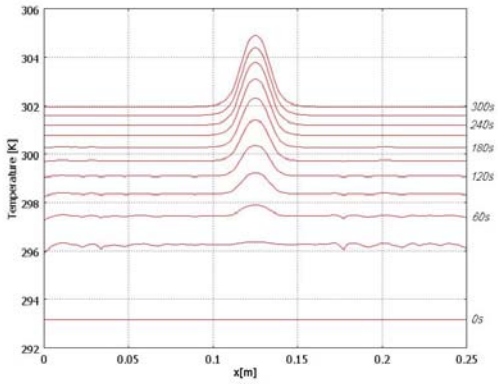

Fig. 4 Time evolution of the temperature along the surface line of the object with subsurface defect irradiated by IR radiation – results from FEM model

To find the optimal time for observation, we will evaluate thermal contrast defined as:

$$C_T(t) = \frac{T_d(t) - T_s(t)}{T_s(t) - T_s(0)} \tag{6}$$

where $T_d(t)$ is surface temperature of defect area,
$T_s(0)$ is surface temperature of sound area before heating pulse is applied,
$T_s(t)$ is surface temperature of sound area at the time *t*.

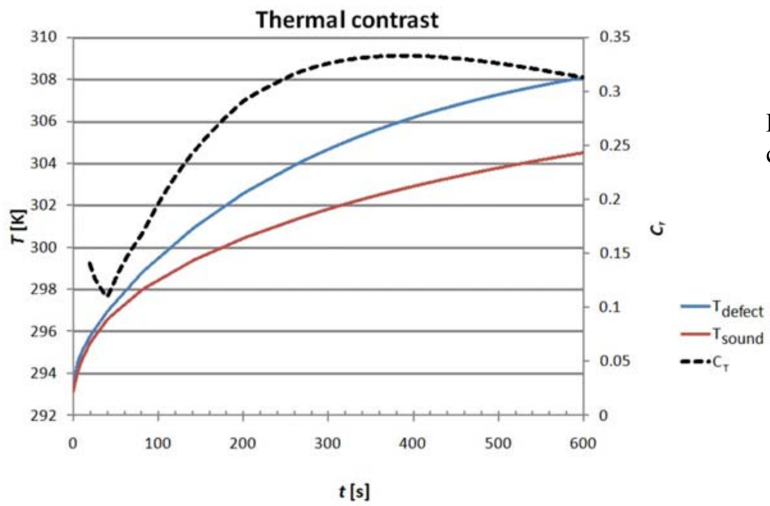

Fig.5 Time dependence of the thermal contrast between defect and sound area

Analysis of the thermal contrast shows in this case local extreme at the time 360s after start of the heating pulse.

4. Experimental results

To prove the theory and FEM modeling results, the experimental active thermographic measurements were done. Set-up of the measuring system was similar as on the Fig.1, thermographic camera NEC San-ei Thermo Tracer TH7102WX was used. The camera is equipped with micro-bolometric array 320x240; camera's instantaneous field of view is 1.6 mrad. Distance of the camera from the object under test was 0.625 m; it corresponds to the spatial resolution 1 mm on the object's surface. For the heat pulse generation two IR panel heaters were exploited. As our team is involved in the non-destructive testing of cultural heritage (frescos, wall paintings); in the first stage the emphasis in the experiments was put on the testing of building materials like plaster, gypsum, concrete, bricks, etc. The testing objects with subsurface defects (filled with air) with the shape as shown on the Fig.2, were made from various constructive materials. The subsurface defect has a cylindrical shape, 20 mm in diameter and is located 5 mm under the surface. Thermogram on the Fig.6 shows the temperature field of the object's surface after IR heating pulse was applied; in the middle of the thermogram a defect area is clearly identifiable.

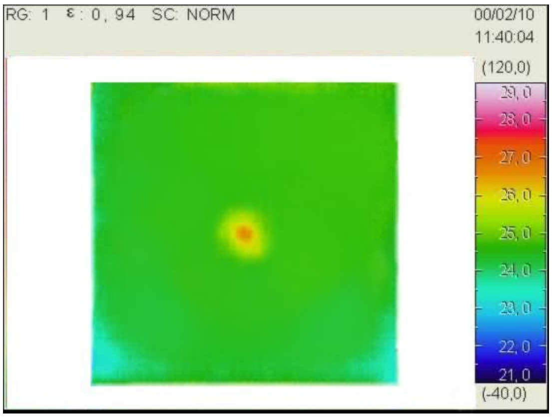

Fig.6 Thermogram of the object under test with subsurface defect in the middle

Temperature difference between defect and sound area is around 2.5 K, as it was predicted by the theory and FEM simulations.

5. Discussion and conclusions

The finite element method was successfully used for the modelling of thermal energy propagation in 3D objects with subsurface defects. Simulation results allow optimization of the active infrared thermographic method, optimal setting of heat pulse parameters and the thermogram observation time. In the active thermography experiments special care should be taken if the emissivity of the surface is non-uniform, or the surface of the object is non-uniformly irradiated by the IR source. This can introduce temperature gradients on the object's surface similar to changes induced by subsurface defects, and therefore these non-uniformities should be eliminated. Results of FEM simulations were experimentally verified in laboratory experiments and the active pulse thermography method was also successfully used at the investigation of frescos and mural paintings (co-operation with restorer J. Dorica).

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